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THESIS

ENERGY HARVESTING FOR SELF-POWERED, ULTRA-LOW POWER MICROSYSTEMS WITH A FOCUS ON VIBRATION-BASED ELECTROMECHANICAL CONVERSION

by

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September 2009

Thesis Co-Advisors: Gurminder Singh
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13. ABSTRACT (maximum 200 words)

Wireless distributed microsensor systems offer reliable monitoring and control of a myriad of applications ranging from machine state and perimeter security to nuclear/chemical/biological and other military applications. Historically, batteries have supplied power to mobile, embedded, and ultra-low power microsensors. While there are many obvious short-term advantages of using batteries, they do have a long-term negative environmental impact. An alternative to batteries exists in harnessing the ambient energy surrounding the system and subsequently converting it into electrical energy. Once a long-established concept, energy harvesting offers an inexhaustible replacement for batteries. Energy-harvesting systems scavenge power from optical, acoustic, thermal, and mechanical energy sources. The proliferation of and advances in wireless technology, particularly wireless sensor nodes and mobile electronic devices, has increased the volume of energy harvesting research as of late. This thesis reviews the principles of the state of the art in energy harvesting systems. We focus on generating electrical power from mechanical energy in a vibrating environment due to its dominant scalability. We explore microelectromechanical systems (MEMS), including electromagnetic, electrostatic, and piezoelectric transduction. Further, power management, trends, suitable applications, and possible future developments are discussed.

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ENERGY HARVESTING FOR SELF-POWERED, ULTRA-LOW POWER MICROSYSTEMS WITH A FOCUS ON VIBRATION-BASED ELECTROMECHANICAL CONVERSION

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ABSTRACT

Wireless distributed microsensor systems offer reliable monitoring and control of a myriad of applications ranging from machine state and perimeter security to nuclear/chemical/biological and other military applications. Historically, batteries have supplied power to mobile, embedded, and ultra-low power microsensors. While there are many obvious short-term advantages of using batteries, they do have a long-term negative environmental impact. An alternative to batteries exists in harnessing the ambient energy surrounding the system and subsequently converting it into electrical energy. Once a long-established concept, energy harvesting offers an inexhaustible replacement for batteries. Energy-harvesting systems scavenge power from optical, acoustic, thermal, and mechanical energy sources. The proliferation of and advances in wireless technology, particularly wireless sensor nodes and mobile electronic devices, has increased the volume of energy harvesting research as of late. This thesis reviews the principles of the state of the art in energy harvesting systems. We focus on generating electrical power from mechanical energy in a vibrating environment due to its dominant scalability. We explore microelectromechanical systems (MEMS), including electromagnetic, electrostatic, and piezoelectric transduction. Further, power management, trends, suitable applications, and possible future developments are discussed.

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I also thank Professors Gurminder Singh and John Gibson for giving me the opportunity to carry out research and write a thesis in the evolving field of energy harvesting. I have truly enjoyed the open-minded research atmosphere within this group.

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I. INTRODUCTION: OVERVIEW OF PROBLEM AND MOTIVATION

A. MOBILE DEVICES AND WIRELESS SENSOR NETWORKS

1. Finite Power

The third wave of computing is marked by the shift from mainframe (first wave) and personal computing (second wave) to what the late Mark Weiser coined *ubiquitous computing*. A subset of this third wave entails embedded peripheral devices such as actuators, sensors, energy sources, and antennas. These wireless sensor network components promise improved utilization of resources, contextual awareness, security, and safety. However, ubiquitous computing and wireless sensor networks present potential concerns about our current reliance on batteries for power.

Chemical cell development has been unable to keep pace with other advances related to ubiquitous computing, as denoted by Figure 1.

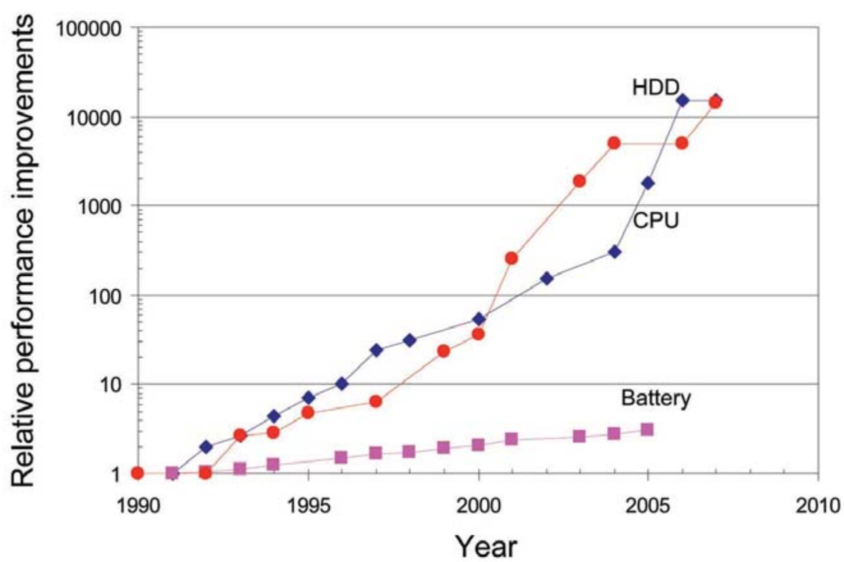

Figure 1. Relative Advances in Energy Density of Li-Ion Batteries Versus Areal Density of HDD and Transistor Density [From 1]

The dearth of battery development is not due to lack of interest. In 1999, the German government committed $1.7 million to stand-up the Fraunhofer Institute for Reliability and Micro-integration. The institute sought to develop cheaper and more efficient lithium-based batteries [2]. Regardless of perceived successes, this initiative failed to provide a means for divorcing wireless sensor networks from a physical link to the world.

No advances in chemical cell technology will completely eliminate its inherent physical limitation of finite power. As such, finite power dominates design considerations of all battery-operated wireless sensor nodes and mobile devices. Despite energy efficient protocols and system partitioning [3], this dependency requires that batteries of a wireless microsystem be recharged or replaced. Consequently, the user becomes quite aware of embedded technology that Mark Weiser intended to disappear from the human conscious. As wireless microsystems continue to grow in ubiquity, so too will battery density and labor costs. Equally, if not more important, the environmental impact of discarding potentially millions of coin-size and bigger batteries becomes irreversible.

2. Need for Infinite Power

Wireless sensor nodes and mobile electronic devices are increasingly becoming the obvious choice for remote data collection and context recognition. Applications for these microsystems extend well beyond monitoring temperature, location, material fatigue and chemical detection. These systems play a particularly vital role in biomedical electronics and wearable computing. This development has not been lost on the Department of Defense (DoD). The U.S. Army and MIT partnered in 2002 to create the Institute for Soldier Nanotechnologies (ISN). One area of research focuses on creating a non-invasive biosensor that not only automates blood analysis but medicinal delivery. In 2007, the U.S. Navy sought development of a miniature vibration mechanical energy harvester to power remote corrosion monitoring sensors on ships and aircraft. Indeed, the DoD is well aware of the potential for wireless microsystems. Like their civilian

counterparts, the DoD discerns tomorrow's necessity for distributed sensing and ubiquitous computing that is free from tethered power.

Figure 2 offers a decisive comparison of vibration-based and solar energy versus conventional battery power. The darkest shade depicts exclusively vibration-based energy while the lesser shaded region represents both indoor and direct photovoltaic energy generation. It is possible to deduce from this figure that design consideration should include the projected lifetime of the electronic application. If the design is to be utilized for only a few years, one could argue that batteries provide the simplest and most adaptable power source. However, the availability of adequate environmental light energy demands consideration as a solution. Nonetheless, should the projected lifetime extend beyond several years and light energy is not readily available, other domains of energy harvesting become attractive solutions.

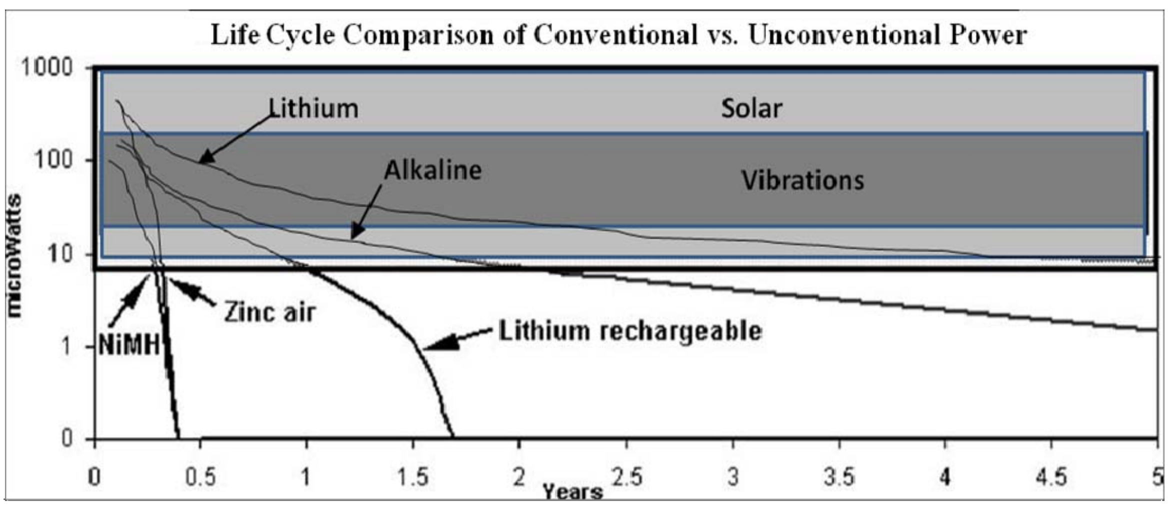

Figure 2. Comparison of Power Densities [From 4]

Advances in integrated circuit (IC) fabrication coupled with novel network protocols have resulted in breaking below the milliwatt threshold for powering wireless microsensor nodes [3]. Inherently, the microsensor's transmission power limits its effective range significantly when compared to a wireless macrosensor. As a result, microsensor nodes form a dense topology transmitting data no more than 10 meters.

The problem of powering potentially dense networks of nodes becomes substantive when considering the expected global ubiquity of wireless sensor networks. Sheer volume disqualifies the procurement and placement of disposable and recyclable batteries. Moreover, environmental implications force the consideration of alternative power sources [5].

B. PROBLEM DESCRIPTION

The objective of this thesis is to identify the energy harvesting technologies best suited for military applications in the domain of wireless network sensors and mobile devices. Candidates for this technology include light, sound, thermal gradients and vibration energy scavenging methods. While this thesis does not pinpoint a single energy domain and harvesting method to satisfy the problem, likely candidates in all energy domains are proposed based on application and environment.

C. THESIS FORMAT

In the succeeding chapter, this thesis provides a thorough history of energy harvesting methods. The fundamentals of energy harvesting methods in optical, acoustic, thermal, and mechanical energy domains are examined. While we do not provide an exhaustive comparison, a broad cross section is offered.

Chapter II provides a broad survey encompassing the state-of-the-art advances in light, sound, thermal gradients and vibration energy scavenging methods. Chapter III highlights viable energy harvesting candidates for strong consideration by both civilian and DoD researchers.

Chapter IV presents information beyond the conversion of energy. Energy harvesting systems must also provide power conditioning, storage, and management. Techniques and principles in these three areas are explored. An algorithm for ensuring energy is readily available in a non-deterministic environment offers a management strategy for all harvesting methods.

Finally, Chapter V concludes with a summary of the presented research and potential for future work. An in-depth look at real-world applications offers insight into tomorrow's emerging technologies. The reader is left with a solid appreciation for the potential for energy harvesting at the micro-level.

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II. HISTORY OF ENERGY HARVESTING

"Because the average power consumption of a wireless sensor network node is expected to be very low, on the order of 50 µW or less, unconventional power sources become plausible alternatives" [6]. By harvesting energy or scavenging power, the environment surrounding the wireless sensor network can be turned into an infinite and immediate unconventional power source. Numerous technologies exist that might enable the micro-sensor node to harness ambient energy. The most fundamental of these energy domains (e.g., optical, acoustic, thermal, and mechanical) are considered in this chapter. While we do not provide an exhaustive comparison, a broad cross section is offered.

A. OPTICAL ENERGY

Solar energy is derived from the radiant light or heat emitted by the sun. Solar radiation represents the most readily available renewable energy source on the planet. Of the 174 PW (174×10^{15} watts) that reach the Earth's upper atmosphere, approximately half penetrates to the surface of the Earth [7]. In 2005, the average global consumption of power was 15 TW (15×10^{12} watts) [8]. It does not require a trained eye to deduce that the sun provides far more power than the world could ever use in the near future.

Depending on the method in which solar radiation is harnessed, solar technologies are generally classified as either active or passive solar. Any use of solar energy that does not include conversion to a different energy domain is considered passive solar energy. One of the more dominant active solar technologies is in the field of photovoltaics (PV). Roughly translated, photovoltaic means "light-electricity." PV utilizes a solar module to couple the photoelectric effect that converts sunlight into a direct current. The mechanisms for this process are referred to as solar cells or PV arrays.

First recorded by French Scientist Edmund Becquerel in 1839, the photovoltaic effect is a simple physical process in which photons from absorbed light excite the electrons of a metallic or semiconductor material [9]. This excitation causes the electron

to move from its molecular position. The result is a change of potential, which inherently induces a current. Figure 3 demonstrates the dynamics of the induced electric field that is created by the junction of two slightly different semiconductor materials.

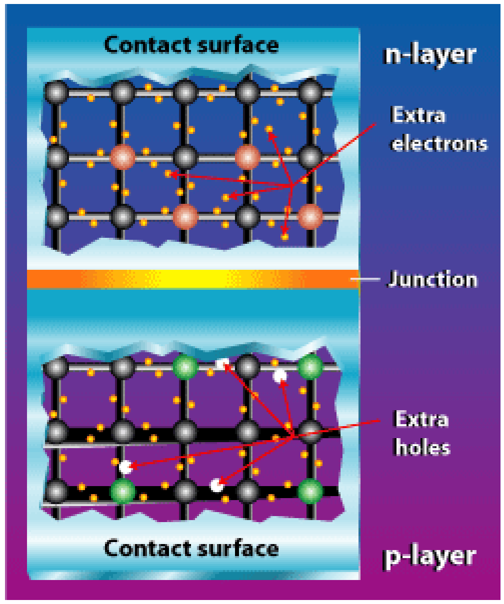

Figure 3. Schematic of Photoelectric Effect [From 10]

As Figure 3 illustrates, one of the layers is an "n-type" semiconductor. Its name connotes an abundance of electrons, which resultantly leads to a negative electrical charge on the entire layer. The other layer is a "p-type" semiconductor. The “p-type” semiconductor gets its positive property from a doping technique. An electron-seeking material (dopant) is introduced to the weakly bound outer electrons of the semiconductor. The dopant atom accepts the semiconductor’s electron thereby forming a “hole” that acts as a positive charge [11]. These holes are free to float throughout the silicon lattice.

While both semiconductors maintain electrical neutrality, the presence of dopants causes n-type silicon to exhibit an excess of electrons and p-type silicon an excess of holes. Combining the p-type and n-type semiconductors together in extremely close contact incites an equilibrium process at the p-n junction. The process is marked by a diffusion of electrons and holes across a space charge region as depicted in Figure 4.

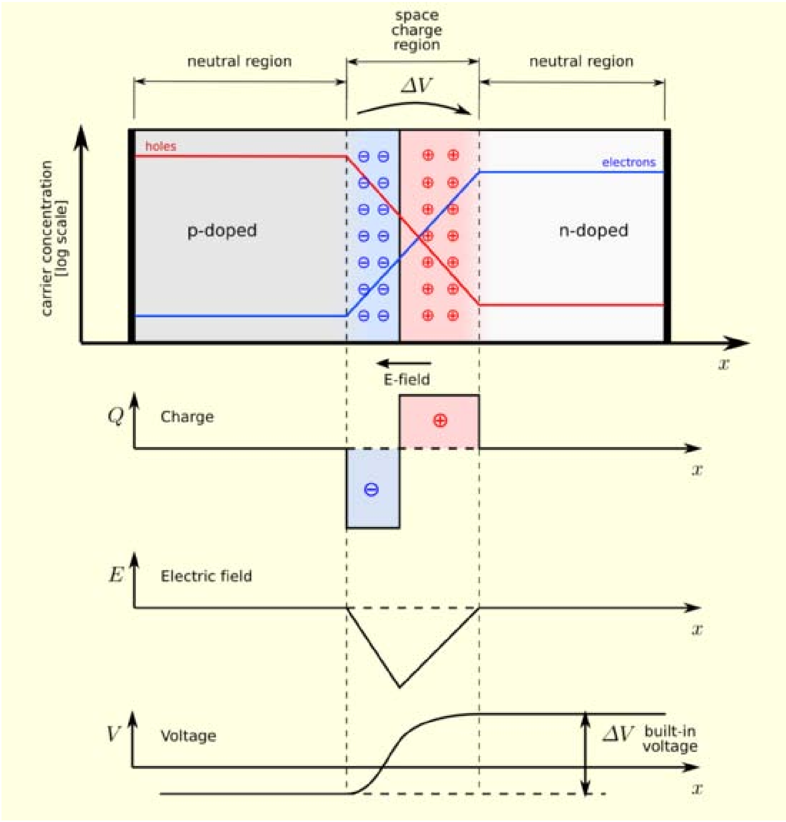

Figure 4. A P-N Junction in Thermal Equilibrium with Zero Bias Voltage Applied. Under the Junction, Plots for the Charge Density, the Electric Field, and the Voltage are Reported. [From 12]

The resultant congregation of positive charge at the n-type boundary and negative charge at the p-type boundary induces an electric field at the space charge region. It is this electric field that produces a current and thus legitimizes the photovoltaic effect as a suitable candidate for an unconventional power source.

It was not until the revolutionary development of Albert Einstein's Quantum Theory in the early 1900s that Becquerel's observation was truly understood [13]. Advances in photoelectric technology by Goldman and Brodsky (1914), Shottky and Mott (1930s), Audobert and Stora (1932), Chapin, Fuller, and Pearson (1954), led to improved transduction conversion efficiencies using silicon, cadmium sulfide, and germanium. During the 1950s, research and development funded by institutions such as

Bell Labs led to efficiencies up to 11%. Due to an average cost of $1,000/watt, most early photovoltaic applications were limited to satellites [14].

Currently, the market average for solar panel energy conversion is between 12-18% [15]. This leads to a power generation potential of 15mW/cm^2. While this power density is promising, effectively harnessing solar radiation is predicated on strict parameters such as direct exposure at near normal angles. PV arrays are adequate for consumer electronics such as calculators, wristwatches, and radios. However, design limitations are further complicated when scaled down to the micro-level. Although a 1 cm^2 PV array is capable of powering an electrostatic MEMS [16], this technology has shown no growth or implementation since demonstrated 14 years ago.

Secondary solar resources, such as biomass, wind, hydroelectricity, and wave power are not reviewed in this study. Literature pertaining to research on current form factors necessary for these technologies is limited for wireless sensor networks.

B. ACOUSTIC ENERGY

Acoustic energy sources may use the energy in sound waves to actuate a MEMS electromagnetic transducer. Most acoustic energy harvesters utilize some variant of an electromechanical Helmholtz resonator. The German Physicist Hermann von Helmholtz built his acoustic resonator during the 1850s for acoustic analysis. The Helmholtz resonator contains a hollow sphere of gas (usually ambient air) connected to the environment by an opening or port. Acoustic input excites the air molecules at the port of the resonator. The elastic nature of the air molecules inside the cavity causes undulation as the internal acoustic pressure attempts to reach equilibrium. Figure 5 depicts a generic schematic of the Helmholtz resonator.

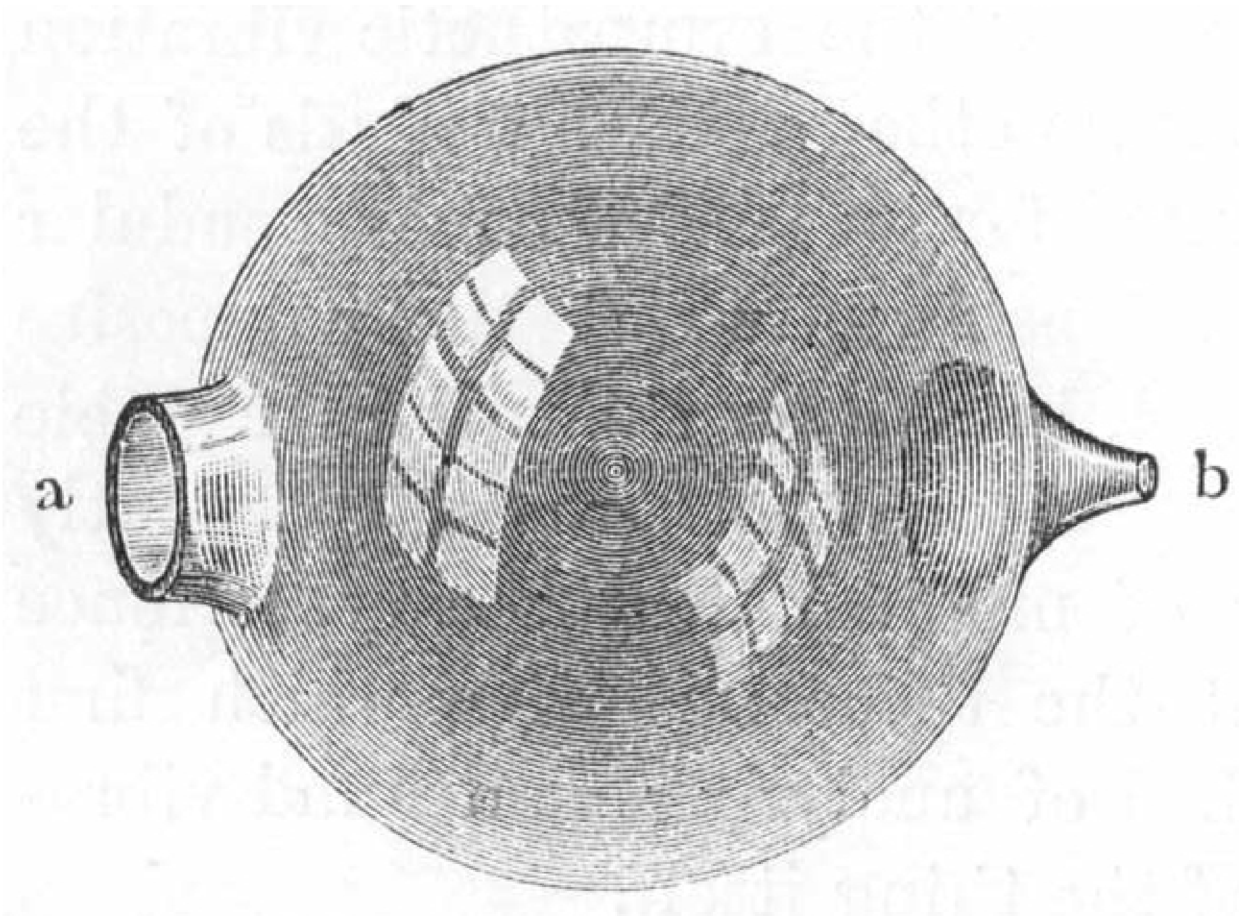

Figure 5. Schematic of Helmholtz Resonator [From 17]

A conceptual rendition of an electromagnetic Helmholtz resonator is offered in Figure 6. Located opposite from the port of the Helmholtz resonator is a piezoelectric backplate. Piezoelectrics will be discussed thoroughly in the latter half of the mechanical section of this chapter. The backplate is actuated by acoustic cavity pressure in a sinusoidal fashion. Acoustic energy is converted first to mechanical energy as the backplate is deformed. Subsequently, mechanical to electrical transduction occurs due to molecular strain of the piezoelectric.

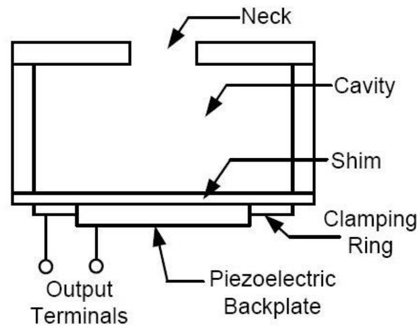

Figure 6. Electromechanical Helmholtz Resonator [From18]

Acoustic energy harvesting experiments by [19] indicate a power density of 0.34μW/cm^2 for an acoustic input of 149 dB. Improved fabrication could potentially achieve a power density of 250μW/cm^2 at 149 dB. While the results show no scaling advantage to miniaturization, the smaller form factor makes this energy harvesting technique an enabling technology for wireless sensor networks. As most acoustic energy harvesters rely on piezoelectrics as a coupling agent, the underlying effect will be discussed in more detail later in this thesis.

C. THERMAL ENERGY

Ambient temperature differentials may also provide a prospective energy source for scavenging. This differential is converted into electricity through a physical phenomenon known as the thermoelectric effect. This effect is an aggregate of three distinct phenomena, the Seebeck effect, the Peltier effect, and the Thompson effect.

1. Seebeck Effect

The Seebeck effect was coined by Estonian-German physicist Thomas Johann Seebeck. He noticed the presence of an electromagnetic field (EMF) when two metals of different temperatures were joined in a complete loop. The voltage induced was on the order of several microvolts per Kelvin.

2. Peltier Effect

Jean-Charles-Athanase Peltier noticed the reverse of the Seebeck effect when a voltage is applied across two dissimilar metallic junctions. Peltier observed that one of the junctions increases in temperature whereas the other decreases [20]. The temperature flux is directly proportional to the magnitude of the current flowing across the closed circuit. As the laws of reversible thermodynamics apply, power densities for the Peltier effect are similar to the Seebeck effect.

3. Thompson Effect

A homogeneous material of different temperatures along its length emits or absorbs heat when subjected to electric current. The British physicist [21] William Thompson observed this effect in 1854 .

4. Thermoelectric Generation

These three thermoelectric effects provide the mechanisms by which thermal energy is converted into electrical energy. Optimal efficiencies degrade based on three non-idealities: parasitic thermal conduction, electrical resistance, and thermal non-uniformity [22]. Nonetheless, NASA successfully implemented thermoelectric generators to power systems on the Voyager. Miniaturization has seen success in micro-fabricated thermoelectric products such as those currently offered by the watchmakers of Seiko. State of the art thermoelectric power densities currently render 50 µW/cm^2 at a temperature difference of 5-K [23]. The last ten years have shown a significant increase in micro-fabricated thermoelectric generator research. While thermoelectric MEMS generators have a very promising future, current low energy conversion efficiency and high cost dissuade candidacy of this energy domain at this time [24].

D. MECHANICAL ENERGY

Mechanical, or vibration, energy generation relies on an environment where a power-scavenging device is subjected to external, preferably sinusoidal, vibrations, such

as walking or a running engine. In such a case, the oscillation generates electricity by utilizing either mechanical strain or relative displacement inside the scavenging system [25]. Micro-scale scavenging systems for vibration energy are based on either force driven or free motion (inertial) microgenerators. The former system is not pursued in this thesis.

Inertial generators are comprised of a suspended inertial proof mass *m*, which displaces *z(t)* relative to a frame as displayed in Figure 7.

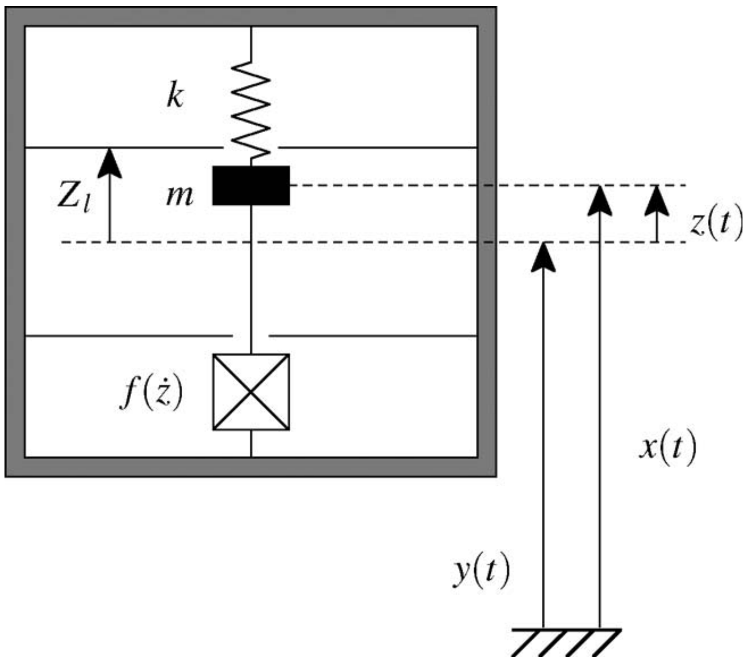

Figure 7. Model of Inertial Generator[From 26]

It is the frame that is actually subjected to external excitation and undergoes absolute displacement *y(t)*. The range of displacement *z(t)* may be either positive or negative depending upon the direction of acceleration. Work is done in opposition to the damping force *f(z)*. This damping force *f(z)* is implemented using a transduction mechanism and naturally opposes any relative motion. Kinetic energy is converted to

electrical energy through this transduction mechanism. This thesis focuses on the three main transduction mechanisms: piezoelectric, electromagnetic, and electrostatic transduction.

1. Inertial Generator Operating Principle

Motion-to-electric energy conversion occurs in seven dynamic steps as shown in Figure 8. Vibration-based mechanical energy is applied in the form of a coupling force. This coupling force either deforms a piezoelectric or accelerates a proof mass. The resultant energy is the work performed by the coupling force. This energy is stored in the generator prior to transduction.

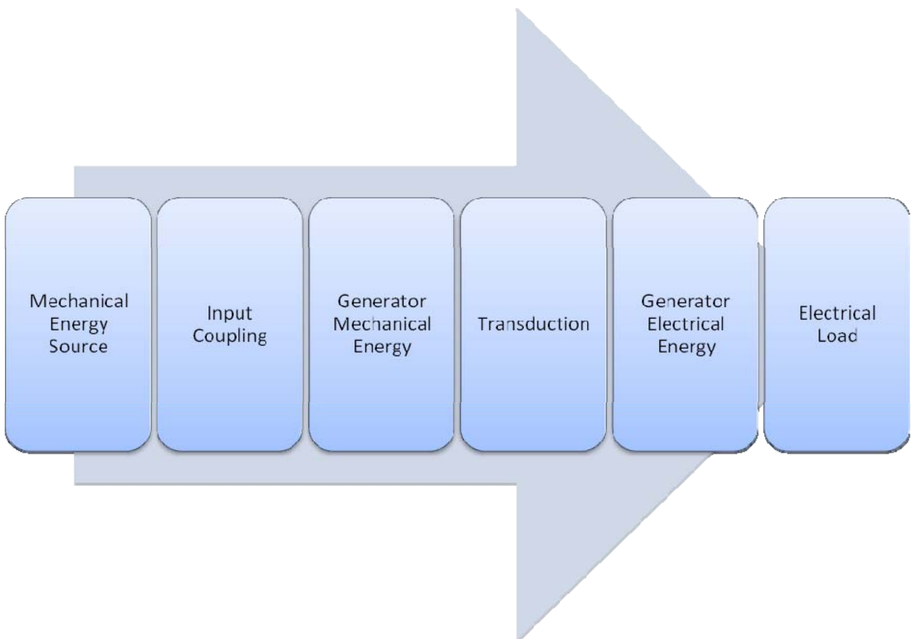

Figure 8. Energy Flow in MEMS Generator

The mechanical energy resident in the generator then undergoes an electro-mechanical conversion through transduction. A transduction force counteracts deformation or acceleration of the input coupling element. This dampening energy loosely equals the work done by the transduction force. Note, in a piezoelectric material, both input coupling and transduction may occur within the same element.

2. Piezoelectric Effect

As early as 1880, two French brothers, Pierre and Jacques Curie, noted a surface charge on crystals of certain minerals when mechanically stressed [27]. The scientific community realized the potential of the discovery and coined the phenomenon after the Greek word "piezein," meaning to squeeze or press. Logically, "piezoelectricity" connotes electricity derived from pressure. A year after the Curie brothers presented the direct piezoelectric effect to the Academy of Sciences, physicist Gabriel Lippmann used the principles of fundamental thermodynamics to mathematically deduce the converse piezoelectric effect. Within a short period of time, the Curie brothers successfully demonstrated the converse piezoelectric effect.

It was not until 1917 that the first serious application for piezoelectric materials was realized. Paul Langevin and fellow French co-workers utilized both direct and converse piezoelectric effects to emit and detect underwater sounds waves. Their sonar transducer made from piezoelectric crystals lead to the field of ultrasonics and hydrostatics [27].

Piezoelectric material use proliferated throughout both World Wars in technologies such as microphones and accelerometers. During World War II, research by the United States, Japan, and the former Soviet Union advanced development of piezoelectric materials with extremely high dielectric (insulator) constants. These research efforts lead to the discovery of piezoelectric ceramics and polymers.

Piezoelectric ceramics consists of perovskite crystals. The structures reside in two distinct crystallographic forms as shown Figure 9. Above a critical temperature known as the Curie temperature, each perovskite crystal morphs into a simple cubic structure with no dipole moment.

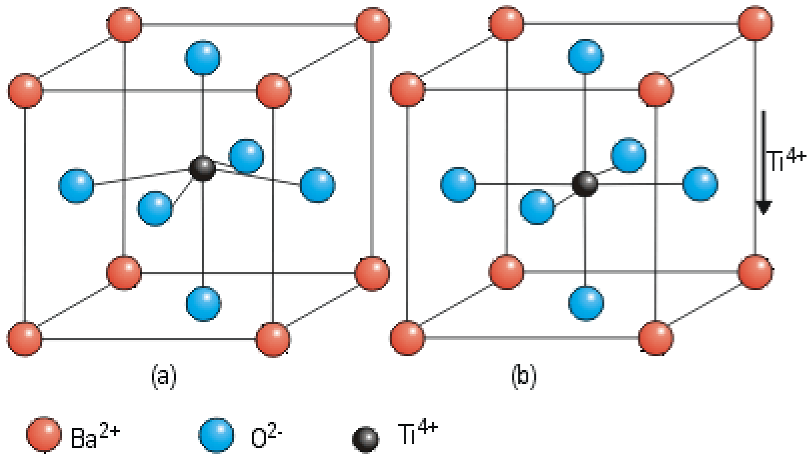

Figure 9. Crystalline Structure of Piezoelectric Ceramic Before and After Polarization [From 28]

Conversely, below the Curie temperature, tetragonal symmetry of the perovskite crystal exhibits a dipole moment. "Domains" are formed by regions of adjoining dipoles sharing local alignment. This arrangement yields an aggregate dipole moment in the domain. The resultant orientation of the net polarization is initially random. Subjecting the material to a strong DC electrical field at elevated temperatures orients the polar domains. The polarization remains as the temperature is reduced. This "poling process," as illustrated in Figure 10, results in the material exhibiting macroscopic piezoelectric properties.

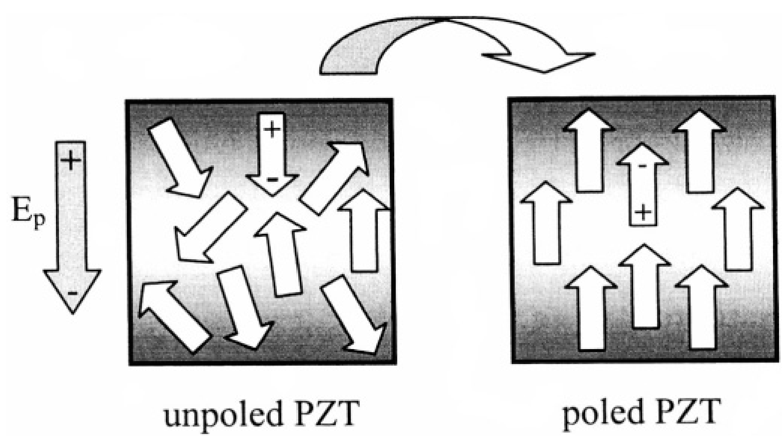

Figure 10. Poling of Piezoelectric (PZT) Material [From 29]

Domains aligned with an applied electric field elongate at the expense of those domains not aligned with the applied electric field. The piezoelectric operates as an actuator as electrical energy is converted into mechanical energy. This transduction mechanism is reversible. As demonstrated by the Curie brothers, mechanical compression or tension applied along the direction of or perpendicular to the dipoles produces an electric field through charge separation. When operated in this fashion, the piezoelectric material acts as a sensor; mechanical energy is converted into electrical energy.

Creative applications in piezoelectric energy harvesting were researched by both Massachusetts Institute of Technology and the University of Pittsburgh in the 1990s [30]. Discerning that humans exert roughly 130 percent of their bodyweight while walking, designers sought to capture the energy released at the foot strike through piezoelectrics. Even with poor electromechanical conversion efficiency, as much as 8.3mW was realized.

Research has yet to completely eradicate the fatigue and stress inherent with the electromechanical interactions of the crystal structures. However, metallic layering and improved processing techniques have been shown to mitigate these factors [31]. State of the art design is currently able to harness as much as 30mW of power [32]. Piezoelectrics will continue to be a viable candidate for actuating, sensing, and harvesting energy at the micro-scale level due to its innate ability to detect even the smallest vibrations.

3. Electromagnetic Effect

The union between electricity and magnetism has been observed by sailors ever since the magnetic compass assisted in nautical navigation. Hermann Melville noted the phenomenon in a chapter titled “The Needle” in the literary classic *Moby-Dick* [33]. As lighting storms approached, Sailors noticed erratic behavior with their compass needles.

In 1600, the English scientist and physician William Gilbert published *De Magnete*. The work elucidates the magnetic properties of the Earth and proposed magnetism and electricity as two distinct effects [34]. Properties of electricity were clarified by experiments of Benjamin Franklin. In 1747, Franklin proposed that electric charge was comprised of an attractive and repulsive electric force [35].

The first hint of true electromagnetic cognizance was evinced by an Italian lawyer and amateur physician named Gian Domenico Romagnosi. In 1802, Romagnosi cited a physical link between an induced current and magnetism [36]. However, credit for the actual discovery of electromagnetism was awarded 18 years later to the Danish scientist Hans Christian Oersted. Upon observing the deflection of a compass needle when near an electric current, Oersted successfully explained the fundamental relationship between electricity and magnetism [37].

Building upon Oersted's discovery that electric current produced a magnetic field, England's Michael Faraday formulated the principle of electromagnetic induction. In 1831, Faraday empirically proved that electric current could be produced through the motion of a magnetic field [38]. The adroit mathematician from Scotland, James Maxwell, unified preceding developments up to 1864 into an accurate theory of electromagnetism known as Classical Electromagnetism. Maxwell established a set of mathematical equations to accurately describe electromagnetic fields [39].

Conventional macroscale electrical generators are primarily based on electromagnetic transduction. This form of transduction realizes power generation through Faraday's Law of Induction. Figure 11 provides a general schematic for the basic operating principle of the electromagnetic transducer.

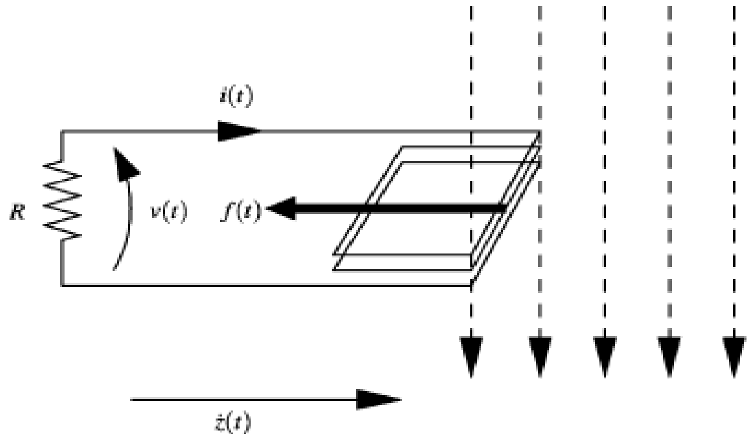

Figure 11. Electromagnetic Transduction Principle Operation [From 40]

Voltage *v(t)* is induced by a change in the magnetic environment. This change is manifested in a variety of techniques such as magnetic field strength fluctuation, drawing coils in and out of magnetic field, and rotating the coils relative to the magnetic field. The voltage produces a current *i(t)* whose own magnetic field opposes change. The strength of this inertial magnetic field is represented by an opposing force *f(t)*. The mechanical work done against this force is reflected in heat (resistance *R*) and stored energy (inductance *I*).

Most electromagnetic energy harvesters today implement a damper using the same principles described by Faraday's Law of Induction and Figure 11. Scaling this transduction mechanism to the micro level introduces key practical considerations. The small geometries inherent in MEMS generators make the rapid flux changes required by strong damping forces complicated to attain. Moreover, the number of coil turns achievable in a MEMS device is limited. Enumerating each technological advance in electromagnetic transduction exceeds the scope of this thesis. However, revolutionary exploits in energy harvesting methods will be discussed in detail under literature review.

4. Electrostatic Effect

In electrostatic generators, two bodies are charged with equal and opposite magnitude (+q and -q). As evinced by Figure 12, an electric field generates capacitive

attraction forces that can be resolved about the three Cartesian directions. Mechanical forces may be employed to work in opposition to these capacitive attraction forces.

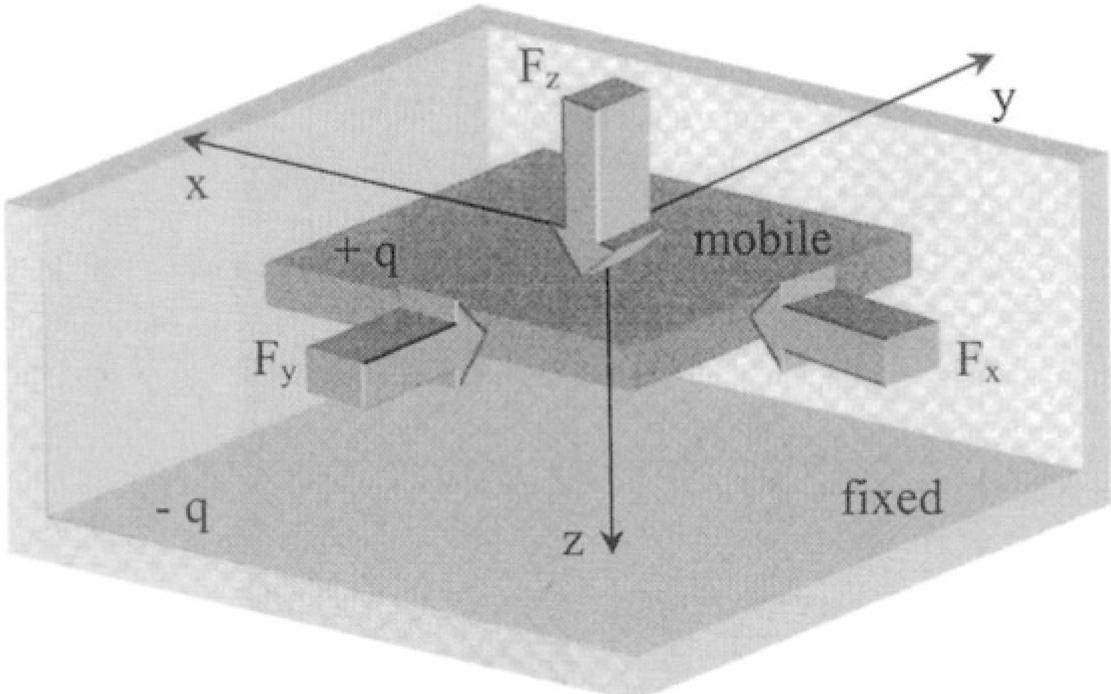

Figure 12. Potential Motion Directions of a Charged Mobile Plate when Attracted by Three Fixed Cartesian Wall-Plates [From 40]

Effectively, electrostatic generators are mechanically variable capacitors. Charging of the capacitor is performed by an external charge. In this case, the microgenerator acts as an electrostatic actuator as electrical energy is converted to mechanical motion. Alternatively, external excitation evokes relative motion along the Cartesian axes, which translates to a capacitive change. In this mode, the system performs as a sensing metric.

Electrostatic actuation and sensing appeal to microgenerators due to the inherent rapid response, sensitivity, accuracy, and relative fabrication costs of the system. Many MEMS devices utilize electrostatic-force principles in a single direction of motion. Figure 13 demonstrates the attractive nature of two oppositely charged plates along a single axis. The question remains as to how movement can be fixed.

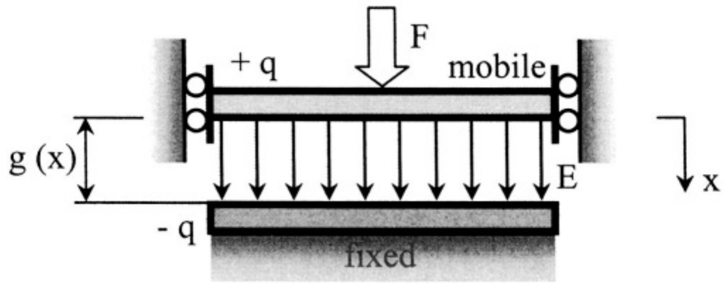

Figure 13. Attractive Force Generated by Electric Field [From 40]

The popular approach for isolating movement along a single axis is to position the mobile capacitive body symmetrically between two balanced forces. Figure 14 offers a two-dimensional schematic showing how the forces along one of the Cartesian axis cancel each other. Thus, only the remaining unbalanced force is subject to movement.

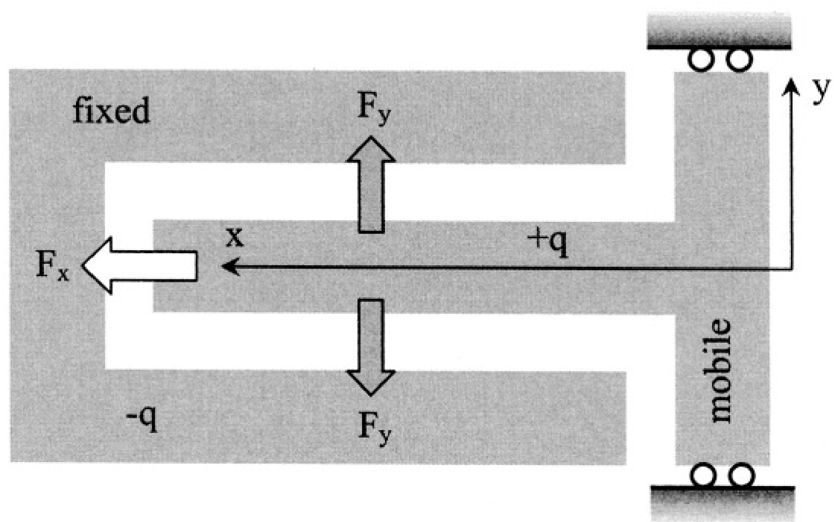

Figure 14. Single Axis Isolation Through Symmetry [From 40]

This concept logically extends three-dimensionally by again balancing forces symmetrically along the out-of-phase-plane.

Base excitation may cause movement along the in-phase plane. Figure 15 provides a model for the principle of operation behind electrostatic transduction.

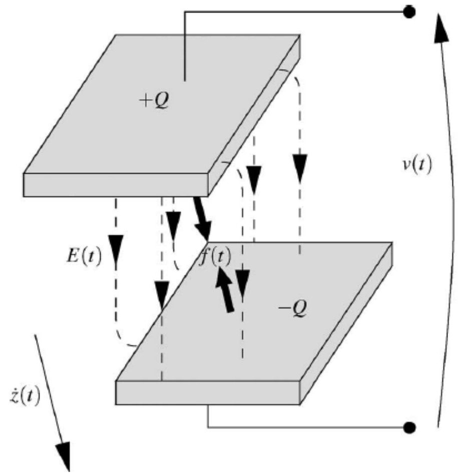

Figure 15. Electrostatic Transducer Constant Charge Operating Principle [From 41]

This parallel plate structure is subject to variable separation. However, the system maintains constant overlap in that the horizontal component of *z(t)* remains zero. As electric field strength *f(t)* is directly proportional to the constant charge *v(t)*, the electric field *E(t)* energy density is independent of the changes in plate proximity. A greater force in opposition to the capacitive attractive force (base excitation) results in plate separation. As a result, the energy expended to perform this mechanical work is stored as potential energy in the electrical field *E(t)*.

MEMS applications are unsuitable for a single pair of charged bodies. In order to amass the requisite energy, multiple pairs are employed in a comb-like configuration. Figures 16 and 17 offer a schematic of this concept in both planar and rotary configurations, respectively.

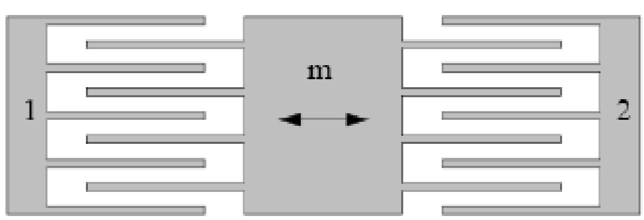

Figure 16. Planar Electrostatic Transduction [From 42]

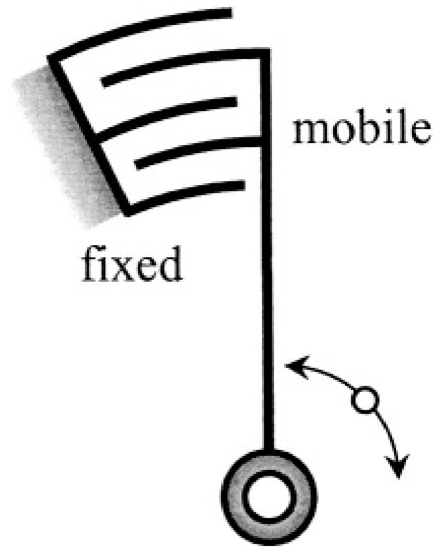

Figure 17. Rotary Electrostatic Transduction [From 40]

Electrostatic transducers possess a unique disadvantage compared to other transduction mechanisms. The need for capacitors requires a precharge, or priming, voltage in order to function properly. Studies have shown the presence of electrets, such as employed for use in microphones and telephones, buried in a dielectric layer may offer a permanent charge [42].

In conclusion, a myriad of technologies exist that might potentially enable an ultra-low power electronic device to operate autonomously on ambient energy. Optical, acoustic, thermal, and mechanical energy domains are introduced to evince their practicality within this thesis's problem set. While not an exhaustive comparison, a broad cross section of fundamentals offers a classification in terms of scalability and usability. The successive chapter will advance this classification by specifically highlighting advantages and disadvantages of each energy domain in terms of micro-scale technologies.

III. LITERATURE REVIEW

The previous chapter provides a historical overview of four major energy harvesting techniques (optical, acoustic, thermal, and mechanical). Of these, optical is the most mature technology. However, because of issues in scalability, it may not be the premier candidate for energy harvesting microsystems. The following chapter reviews key advances in research and the state-of-the-art in energy harvesting. The last section of this chapter highlights breakthroughs in mechanical energy harvesting. We focus on vibration-based electromechanical energy conversion because of its candidacy at the micro-level.

A. OPTICAL ENERGY

Lee et al. (1995) offer a 1 cm^2 solar cell array matched for electrostatic MEMS capable of providing power with an upper voltage potential of 150 V and currents in the nA to µA range. The team used a hydrogenated amorphous silicon (a-Si:H) to optimize their solar array design. Each cell is comprised of a triple layer of P-N junctions coupled with a-Si:H to achieves open circuit voltages of 1.8-2.3 V. One hundred of these single cells (total area of 1 cm^2) interconnected in series produces 150 V and 2.8 µA [16].

In *Third Generation Photovoltaics* (2002), Green argues that second generation solar arrays have realized their maximum potential at 40% efficiency. Green offers a third generation thin-film technology capable of approaching the thermodynamic solar conversion limit of 93%. The text describes options involving parallel configurations of tandem cells to reach higher efficiencies [43].

In a paper submitted to the IEEE Conference on Local Computer Networks (2003), a team from the Free University of Berlin proposes algorithms utilizing solar-aware routing. By adding the solar status of each node as a parameter, route determining algorithms reduced overall power consumption associated with the passing of packets when compared to traditional shortest path algorithms [44].

Li and Chou (2004) submit load matching (maximum point tracking) as a key to solar power conversion efficiency. Their strategy consisted of identifying the optimal runtime load, sunlight condition, and solar panel efficiency curves. A power manager tracks these parameters to yield the maximum power achievable for the profile. Using the load matching strategy, power utilization is improved by 132% compared to traditional solar powered systems. [45].

Raghunathan et al. (2005) develop a mote (Crossbow) plug-in to autonomously manage energy harvesting and storage. As Li mentioned above, Raghunathan et al. cite the importance of a harvesting aware power manager. Their design, coined the Heliomote Board, incorporates such a manager to achieve efficiency levels between 80-84% for the operating range of the 802.15.4 device [46].

B. ACOUSTIC ENERGY

Horowitz et al. (2002) employ an electromechanical Helmholtz resonator with a piezoelectric backplate to reclaim the energy in an acoustic field. Their proof of concept entailed self-powered electret microphone calibration. Laser measured diaphragm displacement coupled with cavity pressure modeled power flow. Conversion efficiency was estimated at 11% and 37% for mechanical to piezoelectric and piezoelectric to electret load, respectively. The authors suggest efficiency could be improved with more complex converter schemes [47].

Horowitz et al. (2006) furthers his research in the field of acoustic energy harvesting by micromachining a Helmholtz resonator with piezoelectric backplate. Empirical results support a power density of 0.34 $\mu W/cm^2$ at 149 dB. Most of Horowitz applications are towards aircraft engine nacelles [19].

C. THERMAL GRADIENT ENERGY

Kiely et al. (1991) from the University of Wales propose fabricating a thermoelectric generator using polycrystalline thermoelements on a quartz substrate. Utilizing silicon integrated circuit technology, the team was able to reduce overall

construction costs while preserving electrical properties similar to a single crystal. According to test results, a 10-fold decrease in the substrate thermal conductivity is realized [48].

Wu et al. (1996) analyzed waste-heat thermoelectric power generators. The team modeled a real waste-heat thermoelectric generator accounting for both internal and external irreversibility. Joulean loss and conduction heat transfer constituted internal irreversibility. External irreversibility was caused by temperature differentials between junctions. Using these factors, the team was better able to predict power and efficiency compared to an ideal thermoelectric generator. Results supported the need for new thermoelectric materials and power module designs [49].

Stordeur et al. (1997) use advanced thermoelectric compound semiconductor thin films to increase power output from the nW range to μW performance. Under a temperature differential of 20 K, prototypes achieve a power output of 20 μW and 4 V. However, upper limits were reached at around 60 μW [50].

Damaschke (1997) introduces a DC-DC converter circuit optimized at the low-voltage and low-power region. His circuit is attached to a bismuth telluride thermoelectric module operating within a 20-^{o}C temperature differential. The combination achieves an upper limit power output of 131 mW and 5 V. More, his low budget prototype performs at 76% of the maximum available power [51].

Stark and Stordeur (1999) introduce a Low Power Thermoelectric Generator (LPTG) capable of a power output up to 23.5 μW and 4.2 V at temperature differentials of 20 K. Their LPTG is based on bismuth telluride technology with decreased substrate thickness and increased film thickness [52].

Zhang et al. (2001) propose, build, and implement a micromachined thermoelectric generator containing a catalytic combustion chamber. Tiny chambers ignite hydrogen and air to power each Polysilicon-Pt thermocouple. Thermocouples then achieve around 1 μW of output power. Temperature differentials approaching 800 K produce up to 10 μW of power per thermocouple [53].

Douseki et al. (2003) demonstrate that the heat from a hand or water is capable of short-range wireless transmission. Their demonstration is realized through a switch-capacitor (SC) type CMOS/SOI DC-DC converter and micromachined thermoelectric module. The author elucidates the difficulty with operating thermoelectric generators at temperatures that lead to negative polarity. To counter this limitation, Douseki employs a converter coupled with a SC capable of always positive power output [54].

Nolas et al. (2006) review recent developments of new concepts and materials concerning low thermoelectric conductivity. Their survey spans from nanostructure to non-microscopic size. They found that improved structural engineering potentially leads to more efficient electron and phonon transport in bulk materials. Changing band structures, energy levels, and electron state density of superlattices improves energy conversion of charged carriers at the quantum level. They conclude that while new materials offer high potentials, conventional glass/electron-crystal materials require more scientific efforts before being dismissed [55].

Yang and Caillat (2006), inspired by NASA's utilization of thermoelectric waste-energy in space systems, sought to recover some portion of the 70% of combustion energy lost in conventional automobile engines. Decades ago, NASA developed radioisotope thermoelectric generators to support space vehicle applications. A schematic of the radioisotope thermoelectric generator used in the Galileo mission is provided in Figure 18.

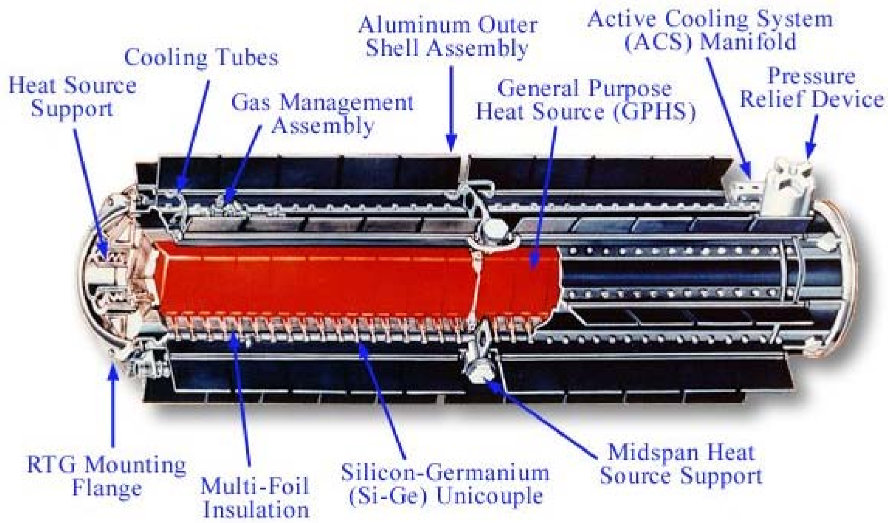

Figure 18. Radioisotope Thermoelectric Generator [From 56]

The radioisotope thermoelectric generator utilizes the aforementioned Seebeck effect. Radioactive decay of an isotope, such as plutonium-238, releases heat that is then converted to electricity through a thermoelectric converter. The subsequent electromagnetic force is used to provide reliable heat and electricity to operate components and science instruments. Yang and Caillat coupled this technology with Chrysler's 1954 attempt to introduce a thermoelectric climate-control system to propose automotive thermoelectric generation. Immediate benefits include the elimination of parasitic loads on the engine drive train as well as replacing current refrigerant-centric systems with a solid state, reversible air conditioning system [56].

Sodano et al. (2007) offer significant advantages of thermoelectric generators over piezoelectric generators in the context of wireless technology. Their proof of concept is illustrated using only the convective (passive) heat transfer of a thermocouple to charge an 80 mAh and 300 mAh nickel metal hydride battery. Their approach is predicated on a miniature greenhouse device to harness the thermal energy from solar radiation [57].

D. MECHANICAL ENERGY

One of the earliest documented experiments in piezoelectric power harvesting was performed by Häsler et al. (1984). They designed and implemented a piezoelectric mechano-electrical generator to power implants such as insulin pumps, glucose sensors, and magnetic valves. Noting thorax displacement during breathing, their design consisted of anchoring a tube between two parallel ribs such that respiratory fixing and contracting strained two stacked piezoelectric sheets within the tube. Figure 19 illustrates a cross sectional diagram of their design.

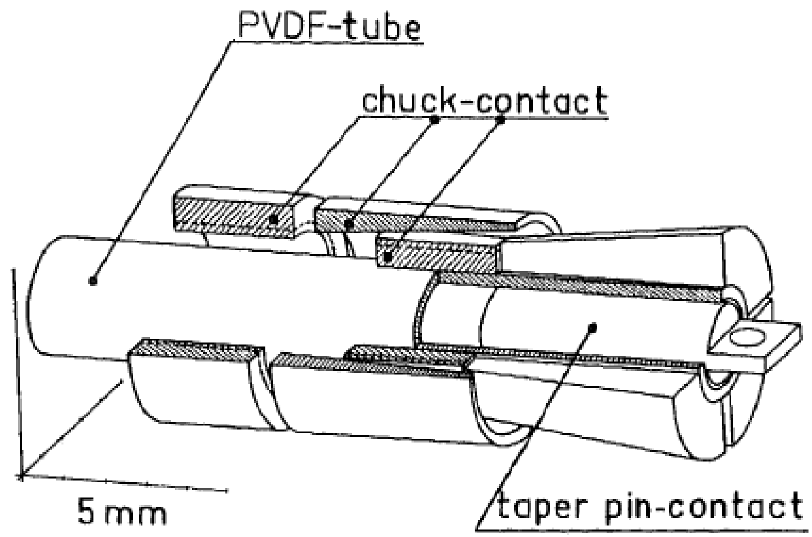

Figure 19. Piezoelectric Mechano-Electrical Transduction Mechanism [From 58]

Simulations achieved an upper power limit of 20 µW based on a 15% power conversion efficiency. Experiments on a dog's lateral thorax region supported a peak at 17 µW. The deviation from expected levels may have been linked to the decrease of displacement from the anticipated 2% to an actual 0.5%. Häsler et al. deem the design insufficient to power implanted devices requiring at least 1 mA of power [58].

Schmidt et al. (1992) propose a piezoelectric polymer wind generator. The team predicts that electrical resonance, coupled with piezoelectric material losses, theoretically achieve a power output of order 100 W/cm^3. The basic piezoelectric methods are

employed using bimorphs under wind-driven mechanical oscillation. Assuming a wind power plant does not exceed an overhead cost of $1000/kW, the team offers their technology could be mass-produced within budget. This is based on the piezoelectric polymer representing no more than 10% of plant costs [59].

Starner et al. (1996) predicted over 10 years ago that ubiquitous computing would cut the tether of the battery. They reviewed numerous power generation methods using the human body. Experiments included capturing body heat at the neck, respiration through masks, and blood pressure via an intravascular turbine. In conclusion, power generation through limb free-motion produced the most potential for powering wearable computing [60].

Williams and Yates (1996) use the General Resonance Generator Theory to derive a set of equations to represent the upper power limit of electromagnetic MEMS. It is understood that inertial-based generators perform as second-order, spring-mass systems. Figure 20 illustrates a simple example of such a system with seismic mass *m* undulating from a spring of stiffness *k*.

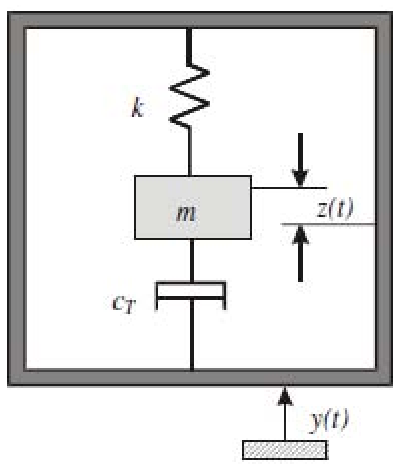

Figure 20. Model of Linear Inertial Generator [From 61]

Energy loss within the system is represented by the damping coefficient, c_T. The damping coefficient is a combination of parasitic loss, c_p, and electrical energy, c_e,

generated by the transduction mechanism. The inertial frame surrounding these components is excited by an external sinusoidal vibration given by

$$y(t) = Y\sin(\omega t), \tag{1}$$

where Y is the amplitude of vibration. Upon external resonant excitation, the seismic mass moves out of phase with the inertial frame and results in a net displacement, *z(t)*. In order to mathematically describe this motion, two assumptions must be established. First, the external vibration's source must be significantly greater in magnitude than the seismic mass. Second, external excitation must be harmonic and infinite. Thus, the movement of the generator does not affect the vibration source. Derived from the dynamic forces on the mass, the differential equation of motion is

$$m\ddot{z}(t) + d\dot{z}(t) + kz(t) = -m\ddot{y}(t), \tag{2}$$

where *y(t)* denotes the displacement of the inertial frame. The succeeding equations are based on the principle that energy is extracted from the relative displacement between the inertial frame and seismic mass. The steady-state solution for the seismic mass is provided by

$$z(t) = \frac{\omega^2}{\sqrt{\left(\frac{k}{m} - \omega^2\right)^2 + \left(\frac{c_T\omega}{m}\right)^2}} Y\sin\left(\omega t - \phi\right), \tag{3}$$

where ϕ is the phase angle expressed as

$$\phi = \tan^{-1}\left(\frac{c_T\omega}{k - \omega^2 m}\right). \tag{4}$$

The harmonic frequency of the system, ω_n, given as

$$\omega_n = \sqrt{\frac{k}{m}}, \tag{5}$$

must equal the excitation frequency in order to achieve maximum power. Because of the characteristics of the system, both the mass and the mass-spring damper are subject to the force expressed as

$$F = -m\ddot{y}(t) \tag{6}$$

Williams and Yates describe the transfer of instantaneous power from the mass, *p(t),* as the multiplication of the magnitude of force on the mass and the velocity of the mass, or:

$$p(t) = -m\ddot{y}(t)\left[\dot{y}(t) + \dot{z}(t)\right]. \tag{7}$$

Mechanical energy is transferred to electrical energy by means of an electrical transducer. As mentioned earlier, the energy extracted by this transduction mechanism combined with parasitic loss constitute the damping coefficient. The net electrical power dissipated (generated) within the damper is expressed as

$$P_d = \frac{m\zeta_T Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta_T \left(\frac{\omega}{\omega_n}\right)\right]^2}, \tag{8}$$

where ζ_T represents the total damping ratio given as

$$\zeta_T = \frac{c_T}{2m\omega_n}. \tag{9}$$

The properties of equation (8) imply that power generation is not affected by transducer type. Moreover, the equation offers that power dissipated (generated) is directly proportional to the cube of the vibration frequency. That said, very low external excitation frequencies may not suffice. The authors assert that the primary design limitation on the power output of an electromagnetic generator is its size. Specifically, device size resultantly limits the magnitude of its seismic mass and displacement potential. That said, an electromagnetic MEMS generator is suitable for embedded systems with a low power requirement. External excitation may range from a few tens to hundreds of hertz. Williams and Yates stopped short of actually fabricating a prototype. [61].

Umeda et al. (1996) investigate electrical power generation using piezoelectric transduction. Their experiment includes measuring the relationship between mechanical

impact energy and the resultant electrical energy after a steel ball stimulates a piezoelectric vibrator. The authors propose a statistically equivalent model to analyze the electromechanical coupling coefficient, mechanical loss, and dielectric loss of the vibrator to ultimately yield the transformation efficiency. The model also attempts to optimize the load resistance [62].

A year later, Umeda et al. (1997) present theoretical and experimental results of a piezoelectric prototype based on their earlier efforts. In this work, the generator's oscillating output voltage is rectified. A capacitor provides a source for storing the resultant rectified voltage. The authors provide an equivalent circuit model to simulate the capacitance and pre-charge of the capacitor. Their prototype ostensibly achieved a maximum efficiency above 35% [63].

Kimura (1998) was issued a patent protecting the production of a piezoelectric generator. A piezoelectric plate produces an AC voltage that is subsequently rectified by means of a Schottky diode. Kimura finally stores the rectified electric potential in a capacitor. Kimura claims his battery-free device could be used as an earthquake alarm. Accordingly, an earthquake of requisite magnitude would displace the piezoelectric plates enough to impart an electromagnetic force. The resultant electromagnetic wave then emits a signal to actuate an alarm [64].

Kymissis et al. (1998) investigate three MEMS generators placed in a shoe for the purpose of environmental energy harvesting. Two of the devices possess a piezoelectric material. The first piezoelectric device attempts to capture the energy released where the sole of the shoe bends. As illustrated in Figure 21, the stave is shaped as an elongated hexagon utilizing a piezoelectric bimorph.

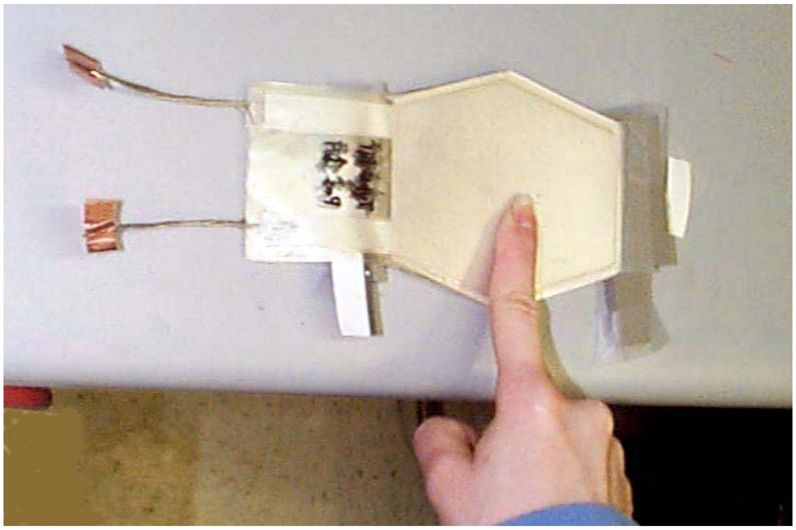

Figure 21. Piezoelectric Bimorph Stave for Insole [From 65]

The second device, displayed in Figure 22, focuses energy capture at the heel strike. The team selects a piezoelectric unimorph developed at NASA.

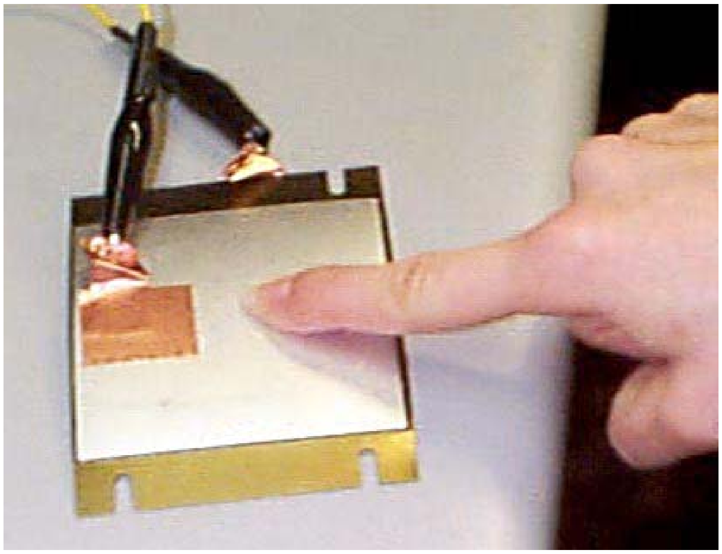

Figure 22. Piezoelectric Unimorph Heel Insert [From 65]

Figure 23 illustrates the third device in which the team elegantly adapts a standard electromagnetic generator to be employed under rotational load.

Figure 23. Rotary Electromagnetic Generator [From 65]

After thorough testing and comparison, a prototype is fabricated to broadcast a digital RFID. Although the rotary electromagnetic device achieved twice the power generation compared to the two piezoelectric devices, integration of the system proved to be the most difficult of all systems. Both piezoelectric devices offer quasi-seamless incorporation into a shoe and generate power at the 10 mW threshold [65].

Goldfarb and Jones (1999) analyze the efficiency of power generation with regard to a piezoelectric stack. One might predict that maximum power generation is realized at the stack's structural resonance. However, the team's analytic model suggests that peak power is achieved several orders of magnitude below resonance. Moreover, their model implies that the energy captured in the piezoelectric stack is returned to mechanical energy as opposed to completing the transfer to electrical energy. Analytic results from the model are substantiated through experiments. The team ultimately concludes that the efficiency of the transduction mechanism is predicated on the magnitude of the input force [66].

Jansen and Stevels (1999) performed work to satisfy a requirement posed by the Industrial Design Engineering of Delft University of Technology in The Netherlands: For what products and how can human power be a viable alternative to batteries in portable

consumer products? The team primarily considers human engagement of muscles as potential power harvesting sources. Human powered systems based on pushing, squeezing, turning, and pedaling are investigated [67].

Allen and Smits (2000) offer a feasibility study of utilizing the Karman vortex to induce oscillations of a piezoelectric membrane coined "eel." The Karman vortex, or eddies, are illustrated along with the eel in Figure 24.

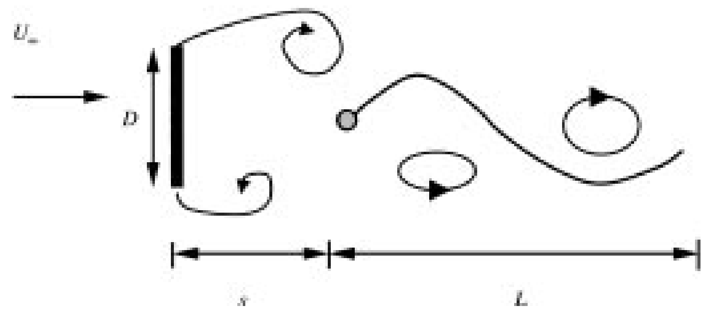

Figure 24. Schematic of Oscillating Piezoelectric Membrane Inside Eddies [From 68]

The team introduced an object into a fluid laminar flow field in order to create unsteady conditions marked by eddies. Placing the piezoelectric eel along these eddies resulted in capacitive buildup [68].

Ramsey and Clark (2001) provide a design study investigating the possibility of using a piezoelectric membrane (1 cm^2) to collect power for an *in vivo* MEMS application. The team successfully loads two piezoelectric plates of differing modes. The 33-mode plate intrinsically offers more power output due to the volume of material. However, the 31-mode operates better in environments similar to the human body and thus provides better conversion efficiency. Ultimately, the 31-mode was shown to harness power for MEMS applications in the μW range for continuous power and the mW range for intermittent power [69].

Elvin et al. (2001) propose that the proliferation of wireless sensors coupled with the decreasing power demand of integrated circuits naturally leads to environmental sources of unconventional power. They analyze a self-powered strain energy sensor within the scope of wireless transmission. Experiments with a composite piezoelectric

beam characterize the wireless sensor response to mechanical strain. Figure 25 shows an analog power harvesting circuit in which a half-diode bridge connects to the capacitor responsible for charge.

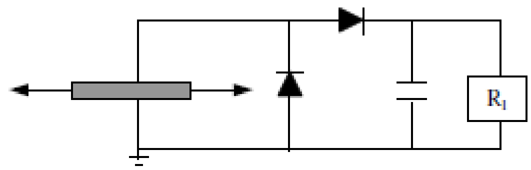

Figure 25. Half Bridge Power Harvester with Leakage Resistance [From 70]

The resistor accounts for the voltage leakage intended in the design. A radio frequency transmitter may adequately constitute this leakage. The team experimentally verifies the strain sensor's dependence on both frequency and magnitude of the applied load. Although the team does not offer potential power densities, they submit that loads between 10 and 20 N suffice to transmit a signal over a distance of 2 meters at 1 MHz. This supports the claim that sensors can collect enough energy from the environment to transmit over a wireless link [70].

Departing from the trend of piezoelectric research, Meninger et al. (2001) model and design a 2163 µm x 2554 µm electrostatic MEMS application capable of achieving over 8 µW of power. The team is able to attain this upper limit by optimizing controller integrated circuits such as power switch sizing and capacitance. Moreover, an ultra-low power delay locked loop-based system is shown to successfully achieve a steady-state lock to the frequency of vibration [71].

Sterken et al. (2002) also discuss electrostatic generators utilizing charged electrets. Unlike Meninger et al., this team employs a duty cycle of 100% as opposed to time periods of no electrostatic conversion. The result is 100 µW at 1,200 Hz for micro-machined capacitors displaced at 20 µm. Another difference in their design is the use of an electret to avoid the need for a pre-charge [72].

Ottman et al. (2002) propose a method for optimizing vibrational energy harvesting through piezoelectric transduction. A step-down DC-DC converter governs

power levels to the electric load. The team experimentally confirms their theory that the optimal duty cycle becomes constant as the excitation frequency increases. This phenomenon greatly simplifies operation of the step-down converter. Ultimately, the converter enables a 325% increase in harvested power. Their design achieved 30.66 mW of power [32].

Sodano et al. (2003) consider the power levels of a few milliwatts too small for practical applications. They prefer to use two piezoelectric designs to charge a nickel metal hydride battery. Although this re-introduces the battery tether, the ability to recharge the battery autonomously preserves the spirit of this thesis. The first model consists of a traditional monolithic piezoelectric plate that proves superior due to its ability to charge various sizes of rechargeable batteries to within 90% capacity. A Macro Fiber Composite (MFC) recently designed at NASA Langley Research Center constitutes the second harvesting device. While the interdigitated electrodes prove more flexible than traditional piezoelectric material, the MFC produces high voltage at low power levels. This results in current levels too low to charge the rechargeable batteries of interest. The piezoelectric device also proves more advantageous over traditional random input signal recharging [73].

Continuing with General Resonant Generator Theory, Beeby et al. (2007) extend Williams and Yates (1996) mathematical analysis of maximum power. As mentioned, maximum power is achieved when the device is excited at harmonic frequency. During such instances, net power dissipation may be given as

$$P_d = \frac{mY^2\omega_n^3}{4\zeta_T}. \tag{10}$$

Excitation acceleration magnitude, A, given by

$$A = \omega_n^2 Y \tag{11}$$

may be substituted in equation (10) to render

$$P_d = \frac{mA^2}{4\omega_n\zeta_T}. \tag{12}$$

Beeby et al. express a transduction mechanism's upper extractable power limit in terms of parasitic and transducer damping ratios as

$$P_e = \frac{m\zeta_e A^2}{4\omega_n\left(\zeta_p + \zeta_e\right)^2}. \tag{13}$$

Extractable power is maximized when both parasitic, ζ_p, and transducer, ζ_e, damping ratios are equivalent $\left(\zeta_p = \zeta_e\right)$. Small amounts of parasitic damping are inevitable and may even be utilized to govern *z(t)*. Based on the above mathematical analysis, the researchers offer new insight into design considerations for inertial generators. Maximum power is predicated on both generator frequency and damping thresholds. These two characteristics must be designed specifically for the application of interest. Too great of an excitation frequency could potentially lead to nonlinear performance and force the generator out of resonance. As power is inversely proportional to the harmonic frequency of the generator one can deduce that the lowest natural frequency is the most desirable. Not only does this maximize power but preserves linear behavior [25].

The chapter highlights noteworthy advances in the field of energy harvesting. Disadvantages and advantages for light, sound, thermal gradient, and vibration-based power scavenging is discussed. The overall opinion from the literature presented is that each domain must be assessed individually in pursuit of the premium method of transduction. However, vibration-based power generation is ostensibly the most adaptable and ubiquitous ambient energy source available for ultra-low power electronic devices. For a more exhaustive review of research, the reader is invited to refer to Sodano et al. [74] and Anton and Sodano's [75] 2007 review of research published more recently. Figure 26 displays many of the noteworthy advances mentioned in this section.

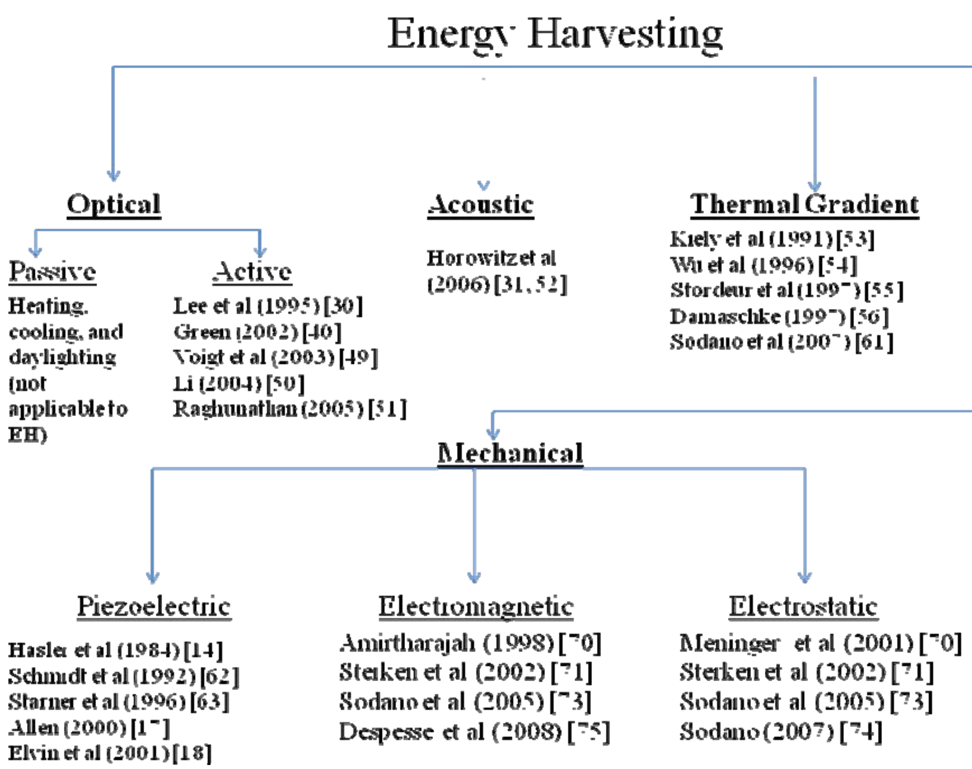

Figure 26. Energy Harvesting Taxonomy

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IV. POWER CONDITIONING, STORAGE AND MANAGEMENT

The previous chapter offers notable achievements in the field of energy harvesting. While a single energy harvesting technique will not suffice to meet the requirements of all microsystems, each technique must take into consideration power conditioning, storage, and management.

A. POWER CONDITIONING

Power conditioning is a technique for manipulating the load delivered to an electrical device. To date, the majority of research in micro-scale energy harvesting focuses on the transduction process while power conditioning is simply reduced to a resistive load. Nonetheless, power conditioning must not be overlooked in the design process. Its demand for thorough consideration is three-fold. First, the unprocessed power from the transduction process will rarely be directly compatible with the electronic device's load. Ottman *et al.* cite the importance of impedance matching for power transfer optimization [32]. Second, input impedance must concur with the input vibration if the extracted input energy is to be maximized [76]. Third, for intermittent energy sources or load sources imparting burst behavior of relatively high energy demand, energy storage devices offer an uninterrupted power supply.

Figure 27 illustrates the output voltage, modeled as an alternating current (AC), of most piezoelectric, electromagnetic and electrostatic micro-generators.

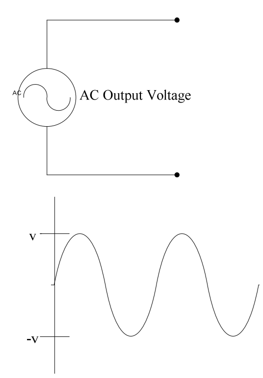

Figure 27. Model of AC Output of Microgenerator [From 77]

One technique for conditioning the voltage in order to ensure compatibility with electronic applications is by incorporating a rectifier. Because photovoltaic and thermoelectric generators produce predominantly positive potentials, this conditioning technique is not necessary.

A full bridge rectifier consisting of four standard diodes converts the AC voltage into a potential usable by most electronics. Figure 28 provides an illustration of the conditioning circuitry used to render this positive potential.

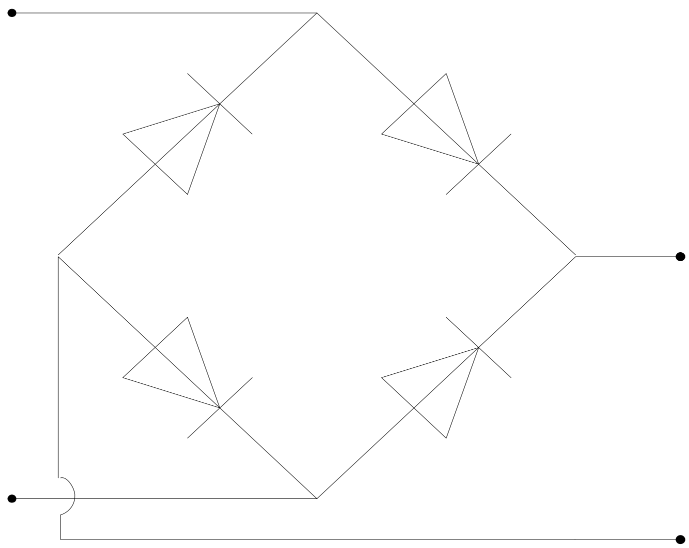

Figure 28. Full Bridge Diode Rectifier [From 77]

It is worth noting that a real diode is not a perfect conductor. As such, it imposes a forward voltage drop thus making the output voltage slightly less that the input voltage. Figure 29 portrays this deviation from an ideal diode with perfect conductivity.

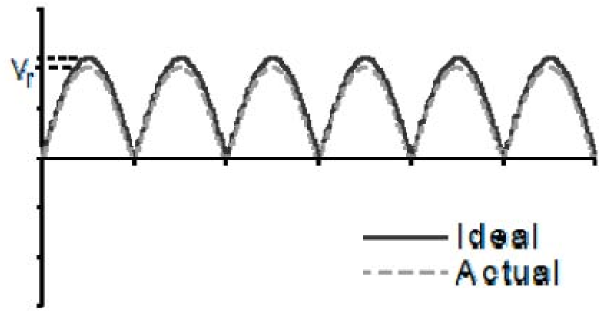

Figure 29. Voltage Output Rendered by Full Bridge Diode Rectifier [From 77]

B. POWER STORAGE

Harvested energy availability is predominantly nondeterministic. This characteristic demands the presence of an energy buffer to satisfy load requirements at all times. Kansal et al. [78] introduce the term “Energy-Neutral Operation” to describe a usage mode in which an electronic application’s level of performance is infinitely supported by the energy harvesting system. Obviously, this system would be subject to hardware failure but the focus is on severing the tether of battery power. In order to evaluate the requirements for the metric coined energy-neutral operation, power from the energy source, $P_s(t)$, and energy consumer, $P_c(t)$, must be abstracted. According to Kansal et al. [78], energy sources may be categorized into the following:

- Uncontrolled but predictable: Such an energy source cannot be controlled to yield energy at desired times but its behavior can be modeled to predict the expected availability at a given time within some error margin
- Uncontrolled and unpredictable: Such an energy source cannot be controlled to generate energy when desired and yields energy at times that are not easy to predict using commonly available modeling techniques or when the prediction model is too complex for implementation in an embedded system
- Fully controllable: Energy can be generated when desired.

- Partially controllable: Energy generation may be influenced by system designers or users but the resultant behavior is not fully deterministic.

The energy consuming activity, or load, being supported may be represented by a sensor node. The consumption profile of this load may be nondeterministic as subsystems independently execute various application layer activities such as sampling, transmitting, and receiving.

Considering power output from the energy source and load at the same instant in time, it is possible to model and analyze the energy conservation in three physical conditions. Each condition will provide limits on $P_s(t)$ and $P_c(t)$ thus ensuring an energy-neutral mode of operation. Kansal et al. [78] define these three conditions as:

- Harvesting system with no energy storage: Energy extracted from the transduction mechanism is directly consumed by the load. No energy buffer exists. The condition for this harvesting scenario may be expressed as

$$P_s(t) \geq P_c(t) \tag{14}$$

  Any energy received at times when $P_s(t) < P_c(t)$ is wasted. Also, when $P_s(t) \geq P_c(t)$, the energy, $P_s(t) - P_c(t)$, is wasted.

- Harvesting system with ideal energy buffer: Often, the energy profiles for generation and consumption may vary enough to warrant a storage mechanism. This scenario presents an ideal energy buffer in which any volume of energy may be stored for an indefinite amount of time. No leakage occurs. For this case, the following expression should be satisfied for all non-negative values of *T*:

$$\int_0^T P_c(t)dt \leq \int_0^T P_s(t)dt + B_0 \forall T \in [0, \infty) \tag{15}$$

  where B_0 is the initial energy stored in the ideal energy buffer. The authors note that equation (14) suffices to ensure equation (15) but not necessary.

- Harvesting system with non-ideal energy buffer: Obviously, the previous two scenarios represent extremes and may not be practical. This final condition provides a more practical scenario where an ultracapacitor acts as an energy buffer. Keeping with the nature of capacitors, the energy storing mechanism is limited in storage capacity and subject to charging efficiency, η, is always less than one. Finally, some fraction of energy is lost due to leakage. The resultant conditions are expressed with the rectifier function, $[x]^+$, being x when greater or equal to zero, else zero:

$$B_0 + \eta \int_0^T \left[P_s(t) - P_c(t) \right]^+ dt - \int_0^T \left[P_c(t) - P_s(t) \right]^+ dt - \int_0^T P_{leak}(t)\, dt \geq 0 \quad \forall T \in [0, \infty) \tag{16}$$

where $P_{leak}(t)$ is the leakage power for the energy buffer. Equation (16) does not account for the depth of the energy buffer. The following expression considers energy buffer depth:

$$B_0 + \eta \int_0^T \left[P_s(t) - P_c(t) \right]^+ dt - \int_0^T \left[P_c(t) - P_s(t) \right]^+ dt - \int_0^T P_{leak}(t)\, dt \geq B \quad \forall T \in [0, \infty) \tag{17}$$

where B represents the energy buffer [76].

These conditions are generalizations of P_s and P_c. In order to express a more practical relationship between P_s, P_c, and B, it is necessary to derive the requirements for the mode presented earlier, energy-neutral operation. Parameters to model characterizations for $P_s(t)$ include average rate of energy generation and variability. Similarly, $P_c(t)$ may be characterized by considering average rate of energy consumption and variability. One approach to characterize these parameters is to modify the token bucket quality of service algorithm established by Shenker et al. (1997) to smooth out the "burstiness" of data injected into a network [79]. Extending this model from simply policing peak rate, average rate, and burst size, one may bound both the minimum and

maximum energy generation (or consumption) of a harvesting system. Kansal et al. offer expressions that sufficiently characterize these parameters:

A non-negative, continuous and bounded function P(t) is said to be a (ρ, σ1, σ2) function if, and only if, for any value of finite positive real numbers τ and T, the following are satisfied:

$$\int_{\tau}^{\tau+T} P(t)dt \le \rho T + \sigma_1 \tag{18}$$

$$\int_{\tau}^{\tau+T} P(t)dt \ge \rho T - \sigma_2 \tag{19}$$

This model may be used for an energy source or a load. For instance, if the harvested energy profile Ps(t) is said to be a (ρ, σ1, σ2) function, then the average rate at which energy is available for long durations becomes ρ1 and the burstiness is bounded by σ1 and σ2. Similarly, suppose Pc(t) is modeled as a (ρ, σ1, σ2) function [78].

C. POWER MANAGEMENT

One of the greatest differences between battery powered devices and energy harvesting devices is that the former's design imperative is to minimize energy consumption [80] or maximize battery lifecycle while meeting performance

requirements. Concerning energy harvesting devices, though rate of availability may be limited, the long-term availability of energy is potentially infinite. Thus, energy-harvesting devices possess unique design considerations that must account for persistent operation. The immediate requirement that must be addressed is how to ensure the lower bound of energy generation satisfies the upper bound of energy consumption in such a manner that energy is not wasted. One solution is to introduce a power management system to mediate the profiles of energy generation and consumption. Traditional power management algorithms for conventional devices simply need information concerning available energy from the battery. Such an algorithm will not suffice for energy harvesting systems.

The ultimate goal of an energy harvesting system power manager is to prevent the system from shutting down due to lack of power. To achieve this goal, the power management strategy must encompass three computations [78]. The first computation instantiates the energy generation model. This model uses previous energy source profiles to predict future profiles.

$$\tilde{x}(i) = \alpha \tilde{x}(i-1) + (1-\alpha) x(i) \tag{20}$$

Where x(i) represents the energy generated during time interval, i. Equation (20) provides the historical average of energy during i. α is a weighting factor less than one that decreases impact of older time intervals. This prediction model is based on an exponentially weighted moving average.

The second computation determines the optimal duty cycle based on the predicted energy from the first computation. Define the sets *A* and *N* as:

$$A = \{ i \mid P_s(i) - P_c \geq 0 \} \tag{21}$$

$$N = \{ i \mid P_s(i) - P_c < 0 \} \tag{22}$$

Set *A* represents time intervals of energy available whereas N represents non-availability. Energy under allocated is given as:

$$\sum_{i \in U} D(i)\left[\frac{P_c}{\eta} + P_s(i)\left(1 - \frac{1}{\eta}\right)\right] + \sum_{i \in A} P_c D(i) < \sum_{i=1}^{N_w} P_s(i). \tag{23}$$

Energy over allocated is given as:

$$L = \sum_{i \in U} D(i)\left[\frac{P_c}{\eta} + P_s(i)\left(1 - \frac{1}{\eta}\right)\right] + \sum_{i \in A} P_c D(i) < \sum_{i=1}^{N_w} P_s(i). \tag{24}$$

The energy deficiency, *L*, invokes a reduction in duty cycles to meet performance optimization. To drive *L* to zero, uniformly decrease duty cycles by δ:

$$\begin{aligned} \delta\,|A|\,P_c &= L \\ \delta &= \frac{L}{|A|\,P_c} \end{aligned} \tag{25}$$

where $|A|$ is the set cardinality operator.

The third computation adapts the duty cycle to meet the predicted energy from the second computation. This step is imperative, as actual energy availability may not be known a priori. Equations (24) and (25) are based on predicted values. The power management system must be able to adapt duty cycles based on actual energy availability to ensure energy-neutral operation. Excess energy, *X*, may be defined as

$$X = \left\{ \begin{array}{l} P_s(i) - P_s^{'}(i) \\ P_s(i) - P_s^{'}(i) - D(i)\left[P_s(i) - P_s^{'}(i)\right]\left(1 - \dfrac{1}{\eta}\right) \end{array} \right\}. \tag{26}$$

The first term denotes the energy differential when the power generated is greater than the power consumed, $P_s^{'}(i) > P_c$. The second condition represents a dearth of available environmental energy, $P_s^{'}(i) \le P_c$. In this case, the energy buffer is accounted for using the efficiency factor, η.

A new quantity is required to account for power usage when the duty cycle is changed through the adaption mentioned in the third computation [78]. Define a quantity

R(j, δ) as follows:

$$R(j,\delta) = \begin{Bmatrix} P_c\delta \\ \delta\left[\dfrac{P_c}{\eta} + P_s(j)\left(1-\dfrac{1}{\eta}\right)\right] \end{Bmatrix} \tag{27}$$

The first condition of equation (27) is satisfied if the power consumed during time interval, *j*, is greater than the power consumed, $P_s^{'}(j) > P_c$. On the other hand, if power generated is less than or equal to power consumed, $P_s^{'}(i) \le P_c$, the second condition is met. The underlying premise of the third computation is to transfer any surplus of energy to the energy buffer for use by future duty cycles with a dearth of available energy. A dynamic duty cycle adaption algorithm, which follows, created by Kansal et al. (2007) attempts to perform this calculation at the end of every duty cycle to ensure energy-neutral operation [78].

```
Iteration: At each time slot do:
if X > 0
  P_sorted = P_s{1,…,N_w} sorted in ascending order.
  Q := indices of P_sorted.
  for k = 1 to |Q|

     if Q(k) ≤ I //slot is in the past

        continue
     if R(Q(k), D_max –D(Q(k))) < X
         D(Q(k)) = D_max
         X = X – R(j, D_max – D(Q(k)))
     else
         //X is insufficient to increase duty cycle to D_max
         if P_s(Q(k)) > P_c
            D(Q(k)) = D(Q(k)) + X/P_c
```

else

$$D(Q(k)) = D(Q(K)) + \frac{X}{\left(P_c/\eta + P_s(Q(k))(1-1/\eta)\right)}$$

if $X < 0$

$P_{sorted} = P_s\{1,\ldots,N_w\}$ sorted in descending order.

$Q :=$ indices of P_{sorted}.

for $k = 1$ **to** $|Q|$

if $Q(k) \leq i$ **or** $D(Q(K)) \leq D_{min}$

continue

if $R(Q(k)), D_{min} - D(Q(k)) > X$

$D(Q(k)) = D_{min}$

$X = X - R(j, D_{min} - D(Q(k)))$

else

if $P_s(Q(k)) > P_c$

$D(Q(k)) = D(Q(k)) + X/P_c$

else

$$D(Q(k)) = D(Q(K)) + \frac{X}{\left(P_c/\eta + P_s(Q(k))(1-1/\eta)\right)}$$

D. CHAPTER SUMMARY

In conclusion, research in micro-scale energy harvesting predominantly focuses on the transduction process. Power conditioning is essentially ignored and represented as little more than a resistive load in the harvesting system. Because most of the output power from vibration-based microgenerators is an AC voltage, energy harvesting systems will most often require rectification for compatibility with practical electronic devices. This requirement demands more attention than a simple resistive load.

The nondeterministic property of rate of energy availability necessitates the presence of an energy buffer to satisfy load requirements at all times. While rate of availability may not be known a prior, it is logical to assume the long-term availability of energy as potentially infinite. With this characteristic of persistence in mind, a management system is required to mediate the profiles of energy generation and consumption.

V. CONCLUSION

A. QUOD ERAT FACIENDUM

1. Powering the Third Wave

Years ago, personal computers helped distribute computing beyond the mainframe. Today, embedded systems and mobile devices usher in the third wave of computing as technology migrates away from the desktop paradigm. The capabilities of these ubiquitous microsystems are profound. However, potential is hampered by their reliance on conventional power sources.

Batteries are often the default power source when mains power is unavailable. Many types of electrochemical cells exist throughout the world. One of the many advantages batteries have over mains power is the significant reduction in hardware costs. However, electrochemical cells pose disadvantages that become rather serious when the battery is miniaturized.

One of the serious design limitations for battery operated electronic devices is finite lifetime. This characteristic requires that batteries be either recharged or replaced. Battery and labor costs become quite significant as electronic devices proliferate in ubiquity. In addition, depending on the application and development, it may not be safe to reach the devices once they are deployed. Additionally, the environmental impact of discarding potentially millions of electrochemical batteries demands serious concern.

Ironically, infinite energy sources pervade the environment around all electronic devices. It is currently possible to energize ultra-low power devices with ambient energy domains such as light, sound, thermal gradients, and vibration. Compared to conventional electrochemical batteries, these energy sources do not saturate the earth with waste, and may also be safer than the physical handling needed to change batteries. Further, they do not require hours of maintenance and inspection.

Current disadvantages of energy harvesting include inconsistent, low, and capricious levels of available power. However, research in industry and the academic community promises to minimize these shortfalls in time.

2. Existing Real World Applications

Today's warfighters already utilize autonomous, wireless microsystems to collect and control superior situational awareness through constant surveillance. These embedded and remotely distributed systems offer persistent power in the field of surveillance, wireless personal area network (WPAN), and structure analysis.

a. Surveillance

Self-powered, remote wireless sensor networks currently improve tactical awareness and facilitate quick response. These remote data collection microsystems utilize thermal, acoustic, optical and mechanical energy-harvesting systems. The DoD and the Department of Homeland Security both utilize energy harvesting technologies in unattended ground and marine sensors. These systems are based on mesh networks consisting of a large volume of nodes (sensors) that fuse single event data to reduce false alarms and calculate intruder trajectory. Unmanned aerial vehicles (UAV) and autonomous underwater vehicles (AUV) currently use energy harvesting microsystems to strengthen force protection.

b. WPAN

The Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA) have provided funding since 1993 for micro-energy harvesting initiatives focused on powering wireless personal area networks. In the near future, body worn energy harvesters will offer wearable authentication and location determining devices to the warfighter. The long duration power offered to these devices will significantly extend the operating life of the applications.

c. Structure Analysis

Energy harvesting systems are currently used to power strain sensors for both civilian and military structures. In the civilian sector, self-powered, ultra-low power microsensors provide years of uninterrupted monitoring of industrial HVAC systems. The DoD currently uses strain-induced energy converters to screen the physical condition of critical parts on ships and aircraft.

3. The Road Ahead

Photovoltaic energy harvesters are currently the most mature of harvesting technologies. Although commercially established on the macro-scale, light availability potentially limits practicality on the micro-scale level. Of the energy sources offered in the thesis, no single energy harvesting method disqualifies all others through overwhelming advantages. The decision to use a specific energy harvesting method depends largely upon the environment and deployment.

For instance, an unattended ground sensor (UGS) or unattended marine sensor (UMS) could operate indefinitely if supplied with power from the sun. Also, one could argue that an energy harvesting system utilizing a thermoelectric microgenerator would be a desirable candidate for powering a GPS chip in an environment conducive to temperature differentials of at least 5 degrees. The hoods of high mobility multipurpose wheeled vehicles (HMMVW) operating in the mountains of Afghanistan measure temperature differentials as high as 20 degrees.

Thermal gradient energy harvesting is not limited to mechanized systems; skin temperature may provide the necessary temperature differential to power microsystems. Along the lines of human-worn microsystems, vibrations from human activity may provide additional ambient energy for scavenging power. In an environment with regular frequency, such as walking, all three transduction mechanisms (piezoelectric, electrostatic, and electromagnetic) offer viable solutions for energy reclamation.

Acoustic energy harvesting, although limited in research, offers potential for capturing the pressure waves that sound energy travels along. Horowitz's design [47] could be extended beyond powering the liner for suppression of engine noise in turbofan engine nacelles. With proven systems already scaled down to centimeter dimensions, these acoustic energy harvesters could capture the ambient noise of military aircraft to power a helmet's embedded intercom communication system.

Advances in integrated circuits continue to lower the power consumption of both military and civilian electronic devices. Coupled with the proliferation of mobile devices and wireless sensor networks, the prospect of completely severing the tether of conventional electrochemical batteries grows increasingly attractive. Today, ultra-low power electronic devices are available for microgenerators utilizing energy harvesting systems. The choice of energy harvesting method depends upon the environment and situation. In the very near future, candidacy will extend to other electronic devices still tethered to conventional electrochemical batteries. The need for the military to look at energy harvesting systems as an unconventional power source is clear.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

Energy harvesting presents an ideal power candidate for distributed wireless micro-systems because of its characteristic to provide power indefinitely. True, the domain of energy harvesting extends far beyond electromechanical energy conversion. It is the author's opinion that there exists an expansive range of both civilian and military applications that could greatly benefit from vibration-based micro-generators. As such, further research on efficient power processing for MEMS generators is needed.

In particular, inertial electromagnetic micro-generators pose significant complexity due to inherent low input voltage thresholds and irregular, non-sinusoidal output. Active tuning to resonant frequency deserves further research. Currently, optimization is achieved by designing the micro-generator based on an input frequency known *a priori*.

Piezoelectric converters offer tremendous potential in micro-scale energy harvesting. However, more research must be done concerning fatigue characteristics and scalability towards implementation on a silicon chip. To realize the latter, efforts must be made to improve the thin-film PZT process.

Energy Harvesting technologies necessitate development in order to realize self-powered, ultra-low power distributed microsystems. The current research offered in this thesis demonstrates that the environment offers immediate sources of power to operate wireless sensor nodes and mobile devices. Nonetheless, no single ambient energy source currently provides the optimal solution for all applications. Therefore, energy harvesting solutions must continue to be researched, developed, and tested. Further, a combination of harvesting techniques, chosen based on the targeted deployment environment, provides the most viable path to a reliable, sustainable renewable energy source.

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LIST OF REFERENCES

[1] B. Chalamala, “Portable electronics and the widening energy gap,” *Proc IEEE*, vol. 95, pp. 2106–2107, 2007.

[2] R. Hahn and H. Reichl, “Batteries and power supplies for wearable and ubiquitous computing,” *in Wearable Computers, 1999. Digest of Papers. The Third International Symposium on,* 1999, pp. 168–169.

[3] W. R. Heinzelman, A. Chandrakasan, H. Balakrishnan, and C. MIT, “Energy-efficient communication protocol for wireless microsensor networks,” *in System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on,* 2000, p. 10.

[4] S. Roundy, P. K. Wright, and J. Rabaey, “A study of low level vibrations as a power source for wireless sensor nodes,” *Comput.Commun.*, vol. 26, pp. 1131–1144, 2003.

[5] F. Liu, S. Horowitz, L. Cattafesta, and M. Sheplak, “Optimization of an electromechanical Helmholtz resonator,” *27th AIAA Aeroacoustics Conference, 2*006.

[6] E. H. Callaway, *Wireless Sensor Networks: Architectures and Protocols,* Boca Raton*:* CRC Press, 2004.

[7] J. A. Duffie and W. A. Beckman, *Solar Energy Thermal Processes*, New York: Wiley & Sons, 1974.

[8] T. Shears, *"Data Centers, Power Consumption, and Global Warming – Will the Web Crash? | Gimmie the Scoop* [Online]. Available: http://www.gimmiethescoop.com/data-center-power-consumption-global-warming-will-the-web-crash. [Accessed: March 10, 2009].

[9] H. Hubbard, “Photovoltaics today and tomorrow,” *Science,* vol. 244, pp. 297–304, 1989.

[10] *"Solar Energy Technologies Program: The Photoelectric Effect,* [Online]. Available: http://www1.eere.energy.gov/solar/photoelectric_effect.html. [Accessed: March 6, 2009].

[11] D. A. Neamen, *Semiconductor Physics and Devices: Basic Principles,* New York: McGraw-Hill Science/Engineering/Math, 2003.

[12] W. Shockley, M. Sparks, and G. Teal, "p-n junction transistors," *Physical Review,* vol. 83, pp. 151–162, 1951.

[13] A. Einstein and L. Infeld, *The Evolution of Physics,* London: Cambridge University Press, 1971.

[14] J. J. Loferski, "The first forty years: A brief history of the modern photovoltaic age," *Prog Photovoltaics Res Appl,* vol. 1, 1993.

[15] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. Srivastava, "Design considerations for solar energy harvesting wireless embedded systems," *in Information Processing in Sensor Networks, 2005. IPSN 2005. Fourth International Symposium on,* 2005, pp. 457–462.

[16] J. Lee, Z. Chen, M. Allen, A. Rohatgi, and R. Arya, "A miniaturized high-voltage solar cell array as an electrostatic MEMS power supply," *Microelectromechanical Systems, Journal of,* vol. 4, pp. 102–108, 1995.

[17] F. Liu, S. Horowitz, L. Cattafesta, and M. Sheplak, "Optimization of an electromechanical Helmholtz resonator," *27th AIAA Aeroacoustics Conference, 2*006.

[18] A. Phipps, F. Liu, L. Cattafesta, M. Sheplak, and T. Nishida, "Demonstration of a wireless, self-powered, electroacoustic liner system," *J.Acoust.Soc.Am.,* vol. 125, p. 873, 2009.

[19] S. B. Horowitz, M. Sheplak, L. N. Cattafesta, and T. Nishida, "A MEMS acoustic energy harvester," *J Micromech Microengineering,* vol. 16, p. 174, 2006.

[20] L. F. Wright and C. C. Wright, "Thermoelectric heat exchanger," U.S. Patent 5584183, December 17, 1996.

[21] J. Chen, Z. Yan, and L. Wu, "The influence of Thomson effect on the maximum power output and maximum efficiency of a thermoelectric generator," *J.Appl.Phys.,* vol. 79, p. 8823, 1996.

[22] S. B. Schaevitz, "A MEMS thermoelectric generator," M.S. thesis, Massachusetts Institute of Technology, Massachusetts, 2000.

[23] T. Huesgen, P. Woias, and N. Kockmann, "Design and fabrication of MEMS thermoelectric generators with high temperature efficiency," *Sensors & Actuators: A.Physical,* vol. 145, pp. 423–429, 2008.

[24] S. Chalasani and J. M. Conrad, "A survey of energy harvesting sources for embedded systems," *IEEE Southeastcon, 2008,* pp. 442–447, 2008.

[25] S. Beeby, M. Tudor, and N. White, “Energy harvesting vibration sources for microsystems applications,” *MEASUREMENT SCIENCE AND TECHNOLOGY,* vol. 17, p. 175, 2006.

[26] P. Mitcheson, T. Green, E. Yeatman, and A. Holmes, “Architectures for vibration-driven micropower generators,” *Microelectromechanical Systems, Journal of,* vol. 13, pp. 429–440, 2004.

[27] G. W. Taylor, *Piezoelectricity,* Gordon & Breach Science Pub, 1985.

[28] F. A. J. MOHEIMANI SR, *Piezoelectric Transducers for Vibration Control and Damping (Advances in Industrial Control),* Springer, 2006.

[29] P. D. Mitcheson, E. K. Reilly, P. Wright, and E. M. Yeatman, “Transduction mechanisms and power density for MEMS inertial energy scavengers,” *in Proceeding of the Fourth International Conference on PowerMEMS,* 2006.

[30] J. A. Paradiso, “Systems for human-powered mobile computing,” *in Proceedings of the 43rd annual conference on Design automation,* 2006, pp. 645–650.

[31] E. K. Reilly and P. K. Wright, “Energy scavenging for body sensor networks,” *in Proceedings of the ICST 2nd international conference on Body area networks table of contents,* 2007.

[32] G. Ottman, H. Hofmann, and G. Lesieutre, “Optimized piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode,” *IEEE Transactions on Power Electronics,* vol. 18, pp. 696–703, 2003.

[33] H. Melville, *Moby Dick: Or the Whale,* Chicago: Northwestern University Press, 1996.

[34] W. Gilbert and P. F. Mottelay, *De Magnete,* New York: Courier Dover Pubns, 1958.

[35] W. Isaacson, *Benjamin Franklin: An American Life,* Simon & Schuster, 2004.

[36] S. Stringari and R. R. Wilson, “Romagnosi and the discovery of electromagnetism,” *Rendiconti Lincei,* vol. 11, pp. 115–136, 2000.

[37] D. Jiles, *Introduction to Magnetism and Magnetic Materials,* New York: CRC Press, 1998.

[38] V. Gourishankar and D. H. Kelly, *Electromechanical Energy Conversion,* New York: Intext Educational Publishers, 1973.

[39] J. C. Maxwell, "A dynamical theory of the electromagnetic field," *Philosophical Transactions of the Royal Society of London*, pp. 459–512, 1865.

[40] N. Lobontiu, *Mechanics of Microelectromechanical Systems*, Springer, 2004.

[41] P. Mitcheson, E. Yeatman, G. Rao, A. Holmes, and T. Green, "Energy harvesting from human and machine motion for wireless electronic devices," *Proc IEEE*, vol. 96, pp. 1457–1486, 2008.

[42] L. Tvedt, L. Blystad, and E. Halvorsen, "Simulation of an electrostatic energy harvester at large amplitude narrow and wide band vibrations," *Simulation*, vol. 9, p. 11, 2008.

[43] M. A. Green, *Third Generation Photovoltaics: Advanced Solar Energy Conversion*, New York: Springer, 2005.

[44] T. Voigt, H. Ritter, and J. Schiller, "Utilizing solar power in wireless sensor networks," *in Local Computer Networks, 2003. LCN'03. Proceedings. 28th Annual IEEE International Conference on*, 2003, pp. 416–422.

[45] D. Li and P. Chou, "Maximizing efficiency of solar-powered systems by load matching," *in Low Power Electronics and Design, 2004. ISLPED'04. Proceedings of the 2004 International Symposium on*, 2004, pp. 162–167.

[46] V. Raghunathan, S. Ganeriwal, and M. Srivastava, "Emerging techniques for long lived wireless sensor networks," *Communications Magazine, IEEE*, vol. 44, pp. 108–114, 2006.

[47] S. Horowitz, T. Nishida, L. Cattafesta, and M. Sheplak, "Characterization of a compliant-backplate Helmholtz resonator for an electromechanical acoustic liner," *International Journal of Aeroacoustics*, vol. 1, pp. 183–205, 2002.

[48] J. Kiely, D. Morgan, D. Rowe, and J. Humphrey, "Low cost miniature thermoelectric generator," *Electron.Lett.*, vol. 27, pp. 2332–2334, 1991.

[49] C. Wu, "Analysis of waste–heat thermoelectric power generators," *Appl.Therm.Eng.*, vol. 16, pp. 63–69, 1996.

[50] M. Stordeur and I. Stark, "Low power thermoelectric generator–self-sufficient energy supplyfor micro systems," *in Thermoelectrics, 1997. Proceedings ICT'97. XVI International Conference on*, 1997, pp. 575–577.

[51] J. Damaschke, "Design of a low-input voltage converter for thermoelectricgenerator," *IEEE Trans.Ind.Appl.*, vol. 33, pp. 1203–1207, 1997.

[52] I. Stark and M. Stordeur, "New micro thermoelectric devices based on bismuth telluride-typethin solid films," *in Thermoelectrics, 1999. Eighteenth International Conference on,* 1999, pp. 465–472.

[53] C. Zhang, K. Najafi, L. P. Bernal, and P. D. Washabaugh, "An integrated combustor-thermoelectric micro power generator," *in Proc. Transducers' 01,* 2001, pp. 34–7.

[54] T. Douseki, Y. Yoshida, F. Utsunomiya, N. Itoh, and N. Hama, "A batteryless wireless system uses ambient heat with a reversible-power-source compatible CMOS/SOI DC-DC converter," *in 2003 IEEE International Solid-State Circuits Conference, 2003. Digest of Technical Papers. ISSCC,* 2003, pp. 388–501.

[55] G. Nolas, J. Poon, and M. Kanatzidis, "R efficent developments in bulk thermoelectric materials," *MRS Bull,* vol. 31, p. 199, 2006.

[56] J. Yang and T. Caillat, "Thermoelectric materials for space and automotive power generation," *MRS Bull,* vol. 31, pp. 224–229, 2006.

[57] H. Sodano, G. Simmers, R. Dereux, and D. Inman, "Recharging batteries using energy harvested from thermal gradients," *J Intell Mater Syst Struct,* vol. 18, p. 3, 2007.

[58] E. Häsler, L. Stein, and G. Harbauer, "Implantable physiological power supply with PVDF film," *Ferroelectrics,* vol. 60, pp. 277–282, 1984.

[59] V. Schmidt, "Piezoelectric energy conversion in windmills," *in IEEE 1992 Ultrasonics Symposium, 1992. Proceedings.* 1992, pp. 897–904.

[60] T. Starner, "Human-powered wearable computing," *IBM Syst J,* vol. 35, pp. 618–629, 1996.

[61] C. Williams and R. Yates, "Analysis of a micro-electric generator for microsystems," *Sensors & Actuators: A.Physical,* vol. 52, pp. 8–11, 1996.

[62] M. Umeda, K. Nakamura, and S. Ueha, "Analysis of the transformation of mechanical impact energy to electric energy using piezoelectric vibrator," *JPN J APPL PHYS PART 1 REGUL PAP SHORT NOTE REV PAP,* 1996.

[63] M. Umeda, K. Nakamura, and S. Ueha, "Energy storage characteristics of a piezo-generator using impact induced vibration," *Japanese journal of applied physics,* vol. 36, pp. 3146–3151, 1997.

[64] M. Kimura, "Piezo-electricity generation device," U.S. Patent 812070, September 1, 1998.

[65] J. Kymissis, C. Kendall, J. Paradiso, and N. Gershenfeld, “Parasitic power harvesting in shoes,” *in Wearable Computers, 1998. Digest of Papers. Second International Symposium on,* 1998, pp. 132–139.

[66] M. Goldfarb and L. Jones, “On the efficiency of electric power generation with piezoelectric ceramic,” *Journal of Dynamic Systems, Measurement and Control*, vol. 121, pp. 566–572, 1999.

[67] A. Jansen and A. Stevels, “Human power, a sustainable option for electronics,” *in Electronics and the Environment, 1999. ISEE-1999. Proceedings of the 1999 IEEE International Symposium on,* 1999, pp. 215–218.

[68] J. Allen and A. Smits, “Energy harvesting eel,” *J.Fluids Struct.,* vol. 15, pp. 629–640, 2001.

[69] M. J. Ramsay and W. W. Clark, “Piezoelectric energy harvesting for bio-MEMS applications,” *in Proceedings of SPIE,* 2001, p. 429.

[70] N. Elvin, A. Elvin, and M. Spector, “A self-powered mechanical strain energy sensor,” *Smart Mater.Struct.,* vol. 10, pp. 293–299, 2001.

[71] S. Meninger, J. Mur-Miranda, R. Amirtharajah, A. Chandrakasan, J. Lang, and C. MIT, “Vibration-to-electric energy conversion,” *IEEE Transactions on Very Large Scale Integration (VLSI) Systems,* vol. 9, pp. 64–76, 2001.

[72] T. Sterken, K. Baert, R. Puers, and S. Borghs, “Power extraction from ambient vibration,” *in Proceedings 3rd Workshop on Semiconductor Sensor Actuator,* 2002, pp. 680–683.

[73] H. Sodano, G. Park, D. J. Leo, and D. Inman, “Use of piezoelectric energy harvesting devices for charging batteries,” *in Proceedings of SPIE,* 2003, p. 101.

[74] H. A. Sodano, D. J. Inman, and G. Park, “A review of power harvesting from vibration using piezoelectric materials,” *Shock Vib Dig,* vol. 36, pp. 197–206, 2004.

[75] S. Anton and H. Sodano, “A review of power harvesting using piezoelectric materials (2003–2006),” *Smart Mater.Struct.,* vol. 16, pp. 1, 2007.

[76] G. Despesse, T. Jager, C. Condemine, and P. D. Berger, “Mechanical vibrations energy harvesting and power management,” *2008 IEEE Sensors,* pp. 29–32, 2008.

[77] J. Farmer, “A comparison of power harvesting techniques and related energy storage issues,” M.S. thesis, Virginia Tech, Blacksburg, VA, 2007.

[78] A. Kansal, J. Hsu, S. Zahedi, and M. Srivastava, “Power management in energy harvesting sensor networks,” *in ACM Transactions on Embedded Computing Systems*, *vol. 6*, *Art 32*, 2007.

[79] S. Shenker, C. Partridge, and R. Guerin, *"Request for Comments: 2212,"* 1997. [Online]. Available: http://www.rfc-editor.org/rfc/rfc2212.txt. [Accessed: July 23, 2009].

[80] A. Sinha and A. Chandrakasan, “Dynamic power management in wireless sensor networks,” *IEEE Design & Test of Computers*, vol. 18, pp. 62–74, 2001.

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